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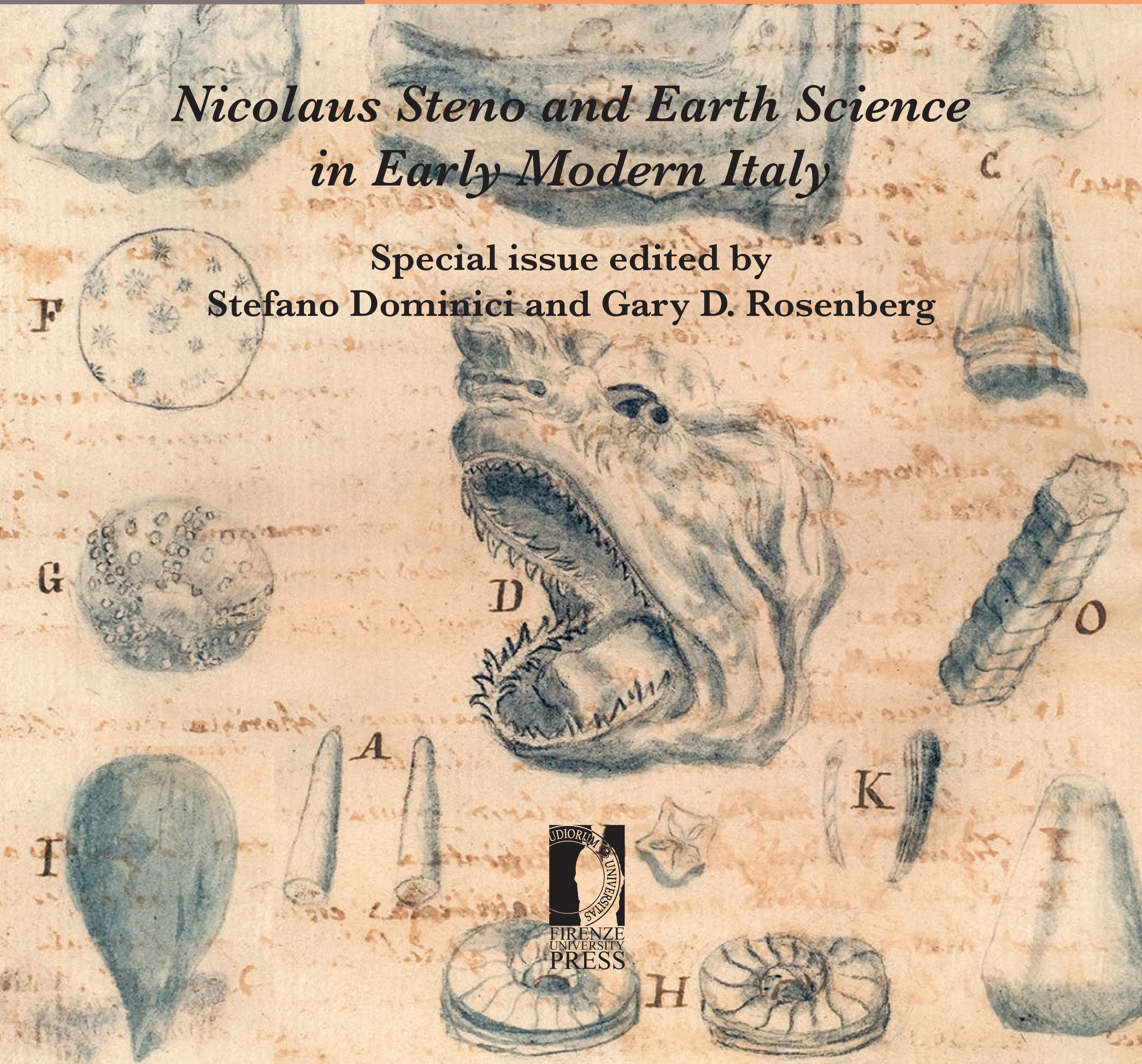

Nicolaus Steno and Earth Science in Early Modern Italy

Special issue edited by
Stefano Dominici and Gary D. Rosenberg

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Introduction: Nicolaus Steno and Earth Science in Early Modern Italy

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> *Asked to what end one should choose to live, Anaxagoras replied "to study the heaven and the order of the whole cosmos"* (Aristotle).[1]

> *Philosophy is written in this grand book – I mean the Universe – which stands continually open to our gaze, but it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometrical figures, without which it is humanly impossible to understand a single word of it; without these, one is wandering around in a dark labyrinth.* (Galileo Galilei, 1623).[2]

> *Why would it not be permitted to hope for great things, if anatomy was transformed so that experimental knowledge would rely only on well established facts, and reason accepted only what has been demonstrated; in other words, if anatomy used the language of mathematics?* (Nicolaus Steno, 1667)[3]

> *Galileo's telescope did not prove the validity of Copernicus' conceptual scheme. But it did provide an immensely effective weapon for the battle. It was not proof, but it was propaganda.* (Thomas Kuhn, 1957)[4]

> *Facts contain ideological components, older views which have vanished from sight or were perhaps never formulated in an explicit manner.* (Paul Feyerebend, 1975)[5]

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[1] Aristotles, *Ethica Eudemia*, in H. Diels, W. Kranz, *Die Fragmente der Vorsokratiker*, Zürich, **1951**, 59 A 30.
[2] G. Galilei, *Il saggiatore, nel quale con bilancia esquisita e giusta si ponderano le cose contenute nella libra astronomica e filosofica di Lotario Sarsi Sigensano*, Rome, Mascardi, **1623**. Quote taken from translation in S. Drake, *Discoveries and opinions of Galileo*, New York, Doubleday & Company, **1957**, pp. 237-8.
[3] N. Stensen, *Canis Carchariae Dissectum Caput,* Florence, Stella, **1667** (*Canis Carchariae* in following notes). English translation in T. Kardel, P. Maquet, *Nicolaus Steno, biography and original papers of a 17th century scientist*, 1st edition, Heidelberg, Springer, **2013**, 594 p.
[4] T. Kuhn, *The Copernican revolution; planetary astronomy in the development of Western thought*. Cambridge, Harvard University Press, **1957**, 297 p.
[5] P. Feyerabend, *Against method: outline of an anarchistic theory of knowledge*. London, New Left Books, **1975**, 339 p.

INTRODUCTION

A group of scientists interested in history of science and fascinated by the figure of Nicolaus Steno (1638-1686) gathered in Florence for the 350th anniversary of the publication of his *De solido intra solidum naturaliter contento prodromus dissertationis*. A public conference held at Palazzo Fenzi on 16 October 2019 and a geological fieldtrip on the following day were occasions to discuss different points of view on the last published work of the Danish natural philosopher, dedicated to "solids naturally enclosed in other solids" (*De solido intra solidum naturaliter contento*, or *De solido* in short). The title of the gathering, "Galilean foundation for a solid earth", emphasized the philosophical context that Steno found in Florence, where in 1666-1668 he established tight human and philosophical bonds with renowned Italian disciples of Galileo Galilei and members of the Accademia del Cimento. The word "philosophical" then had a different emphasis than it has today.

Born and educated in Copenhagen for a medical degree, student in the hotbed of radical thinkers that was Amsterdam and public debater on human anatomy in Leiden and Paris, Steno was already famous when he moved to Tuscany at the age of 28, in 1666. There he found a new type of "anatomical theatre" to carry out the first ideal dissection of the earth and, based on his new and original observations, he wrote a book that is considered a cornerstone of modern geoscience,[6] marking the passage from the late Renaissance understanding of nature, to a modern, geometric approach to the study of strata, mountains, minerals and fossils. During the Renaissance and early modern period geological objects such as fossils and minerals mattered in the first place for their practical properties, essentially for medical purposes, or out of simple curiosity. As such they belonged to the field of natural history and were studied and collected mainly by physicians and apothecaries. Natural history (from Latin *historia*, and Greek ἱστορία, meaning research, knowledge) was a knowledge production tool concerned with the description and classification of natural things, not simply with the record of their past states, as the modern usage of the word "history" implies.[7] In *De solido* the same objects became instrumental to a reasoning that belonged to philosophy of nature, also called "physics", a vast field concerned with the study of overarching laws of nature. The works of Francis Bacon (1561-1626) in England, Galileo Galilei (1564-1642) in Italy and René Descartes (1569-1640) in France had radically transformed the point of view of natural philosophers, bringing observation and mathematics to the forefront. As a student of medicine in Copenhagen, Steno came to study fossils and minerals as a natural historian. Both his anatomical and geological writings, however, clearly show that in Florence he developed mathematics as a tool of the philosopher merging the two fields of knowledge. Since he shared this approach with the many disciples of Galileo connected with the Medici court, the question remains why he decided to move and live in Florence during these crucial years of his life.

During Galileo's lifetime, natural philosophy was undergoing a transformation from being based on the textual analysis of classical philosophers, eminently Aristotle (384-322 BC), to become an empirical science based on observation and measurements, aided by technological advancement and qualified by mathematics.[8] The passage from placing authority on words (of ancient philosophers) to placing it on numbers (collected by the new philosophers) was a slow process taking place simultaneously in several European courts.[9] If mathematics were already used by ancient and medieval natural philosophers to directly represent physical phenomena, modern scholarship recognizes that "no other episode in the history of Western science has been as consequential as the rise of the mathematical approach to the natural world".[10] Galileo had shown that to be a natural philosopher meant to be a mathematician and that, if physical phenomena could not always be translat-

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[6] The consequences of Steno's works in the subsequent development of disciplines such as geology and paleontology still need to be freed from anachronistic and teleological tales of "founding fathers" that "fix principles".

[7] The very name of "Museum of Natural History", given in 1775 in Florence to the institution that housed the 2019 conference, testifies that more than a century after *De solido* natural history was still concerned with organising the products of nature, irrespective of the chronological order of their origins (in a sense, "history" here is a "fossil" word). The modern concept of history as a unidirectional and irreversible process developed starting from the end of the eighteenth century, at the height of the Enlightment, with the influential works of Nicolas de Condorcet (1743-1794) and Thomas Malthus (1766-1834).

[8] Until then applied mathematics were generally considerd of a lower status, because "rather than giving true causal explanations of physical phenomena, rooted in the real natures of the things involved, they just coordinated quantities": P. Dear, "The mathematical principles of natural philosophy: toward a heuristic narrative for the scientific revolution", *Configurations*, **1998**, *6*, pp. 173-193. During this transition, "perspective painting, ballistics and fortification, cartography and navigation prepared the ground for Galileo, Descartes and Newton": D. Wootton, *The invention of science: a new history of the scientific revolution,* Harper Collins, New York, **2015**, 784 p.

[9] P. Dear, "Totius in verba: rhetoric and authority in the early Royal Society", *Isis*, **1985**, *76*, pp. 144-161.

[10] G. Gorham, B. Hill, E. Slowik, "Introduction", in *The language of nature: reassessing the mathematization of natural philosophy in the seventeenth century* (Eds. G. Gorham, B. Hill, E. Slowik, K. Waters), Minneapolis, University of Minnesota Press, 2016, pp. 1-3.

ed into simple mathematical laws, this was simply a sign of the complexity of the mathematical order of nature.[11] The new natural philosopher had therefore to find new mathematical approaches, a mission that Galileo had handed down to the younger generation.

De solido appeared more than a century before a science of geology became a distinct field of knowledge.[12] Three hundred and fifty years after that complex historical transition began, participants at the 2019 Florence conference recognised the necessity to contextualise Steno's observations in Tuscany and to explore what factors drove his new interests and what philosophical approach he adopted.

GALILEO GALILEI

More than a sudden event, the "Scientific Revolution" is generally considered a period spanning 1543 and 1704. In 1543 Vesalius published his anatomical atlas, *De humani Corporis Fabrica*, and Copernicus sent his letter, known as *De revolutionibus orbium coelestium*, to the Pope. The publications marked achievements in observational and mathematical science, the former scientifically depicting human anatomy and the latter proposing to replace the Aristotelian, geocentric model of the cosmos with the heliocentric model. In 1704 Isaac Newton (1642-1726) published his *Opticks*.[13] Based on the residual strength of classical models, this period can be divided into the Scientific Renaissance (roughly the sixteenth century) and the true Scientific Revolution (approximately seventeenth century).[14] Whatever the interval, the innovative approach to the study of the cosmos by Galileo Galilei (1564-1642) represents a discontinuity with the method of predecessors. Since the very late 1650s Galileo's new philosophy came to be qualified as "experimental" because it was based on observational evidences collected through designed experiments[15] which allowed reading "the book of nature" by the use of mathematics, particularly geometry. This took place in addition or in opposition to the approach inherited from Renaissance philosophers who relied on the analysis of authoritative textual resources.[16]

As a young man, in Pisa and Florence, Galileo practiced mathematics, a discipline in which he stood high, suggesting mathematics was more autoritative in the study of physics than the texts of Aristotle and Aristotelians. In Padua, where he taught geometry, mechanics and astronomy, he started an instrument business, a new science of motion and the study of the skies, offering anti-Aristotelian explanations of celestial phenomena and regarding heliocentrism as preferable.[17] In 1609 he built his first "telescope" to make distant objects appear much closer. The telescope allowed for crucial observations described in *Nuncius sidereus* ("the starry messanger"), of 1610,[18] and to convince his skeptics of the validity of his assertions about the Moon and other heavenly bodies. In the words of a twentieth-century scholar: "Galileo's telescope changed the terms of the riddle that the

[11] C. R. Palmerino, "Reading the book of nature: the ontological and epistemological underpinnings of Galileo's mathematical realism", in ref. 10, pp. 36-50. Regarding the famous passage from Galileo's *Assayer* (ref. 2), Palmerino observes that "the chief function of Galileo's use of the metaphor of the book of nature is precisely that of contrasting the exact and 'obligatory' character of mathematical language to the imprecise and arbitrary character of verbal language". On this contrast see also D. Sepkoski, "Nominalism and constructivism in seventeenth-century mathematical philosophy", *Historia Mathematica*, **2005**, *32*, pp. 33-59: "early modern natural philosophers did not separate mathematical and scientific pursuits from more general questions in philosophy, so understanding the philosophical basis of their beliefs gives important insight into the development of contemporary mathematical natural philosophy."

[12] M. J. S. Rudwick, *Bursting the limits of time: the reconstruction of geohistory in the Age of Revolution*. Chicago, University of Chicago Press, **2005**, 708 p. The work of Steno was not connected to the emergence of modern geology.

[13] The use of the word "modern" has changed in time and the concept of "scientific revolution" was introduced only in the twentieth century. For an overview see A. Cunningham, P. Williams, "De-centring the 'big picture': the origins of modern science and the modern origins of science", *The British Journal for the History of Science*, **1993**, *26*, pp. 407-432, and L. A. Orthia, "What's wrong with talking about the scientific revolution? Applying lessons from history of science to applied fields of science studies", *Minerva*, **2016**, *54*, pp. 353-373. See also P. Dear, and D. Wootton, ref. 6.

[14] P. Dear, *Revolutionizing the sciences. European knowledge and its ambitions, 1500-1700*. Princeton, New Jersey, Princeton University Press, **2001**, 200 p. According to other historians the turning point was the discovery of a supernova by Thyco Brahe (1546-1601), proving that the skies are not fixed: "Ptolemaic astronomy was unaffected by Copernicus; it went into crisis with the new star of 1572" (D. Wootton, ref. 8).

[15] Experimental natural philosophy, involving "the collection and ordering of observations and experimental reports with a view to the development of explanations of natural phenomena based on these", is sometimes portrayed as an opposition to speculative natural philosophy ("the development of explanations of natural phenomena without prior recourse to systematic observation and experiment"): P. R. Anstey, "Experimental versus speculative natural philosophy", in *The science of nature in the seventeenth century: patterns of change in early modern natural philosophy* (Eds. P.R. Anstey, J.A. Schuster), Dordrecht, Springer, **2005**, pp. 215-242. Against this dichotomy, and reification of philosophy in general, see D. Levitin, "Early modern experimental philosophy. A non-anglocentric overview", in *Experiment, speculation and religion in early modern philosophy* (Eds. A. Vanzo, P. R. Anstey), New York, Routledge, **2019**, pp. 229-291.

[16] P. Dear, refs. 6-7. For a general background on the historiography of mathematization see also G. Gorham, B. Hill, E. Slowik, ref. 10.

[17] J. L. Heilbron, *Galileo*. New York, Oxford University Press, **2010**, 508 p. This is an excellent biography of Galileo and a source also for other subjects dealt with in the present paper.

[18] M. Gargano, "Della Porta, Colonna, and Fontana: the role of Neapolitan scientists at the beginning of the telescope era", *Journal of Astronomical History and Heritage*, **2019**, *22*, pp. 45-59.

heavens presented to astronomers, and it made the riddle vastly easier to solve, for in Galileo's hands the telescope disclosed abundant evidence for Copernicanism."[19] Galileo himself was aware of his role in society as a philosopher of nature: "beginning with the publication of his *Starry Messenger* in 1610, Galileo took care – through the letters he wrote, the works he published, and the attention he paid to the preservation of his papers – to portray himself as the instigator of a new way of studying nature".[20] By 1623, when he published his *Il Saggiatore* (The assayer), he could safely claim that "philosophy is written in this grand book – I mean the Universe – which stands continually open to our gaze, but it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometrical figures, without which it is humanly impossible to understand a single word of it; without these, one is wandering around in a dark labyrinth."[21]

ACCADEMIA DEI LINCEI

In 1611 Galileo joined the Accademia dei Lincei ("Academy of the Lynxes") in Rome, which had been congregating there since 1603 around the figure of the young natural philosopher Federico Cesi (1585-1630). The Lincei, and Galileo with them, promoted knowledge about new discoveries, starting with astronomy,[22] but also including plants, animals and minerals. Thanks to refined Dutch instruments, in 1625 the Lincei published a study on insects including the first printed illustration made with the aid of a microscope, also introduced in the Accademia by Galileo.[23] This group included Italians and foreign members, and formed an interface between learned men pursuing scholarship, like the austere Cesi, and those with more practical interests like the German Johann Faber (1574-1629), in contact with physicians, apothecaries and surgeons.[24] Their plan for the diffusion of knowledge culminated in 1623-1627 with the publication of the *Rerum Medicarum Novae Hispaniae Thesaurus* ("History of Mexican plants, animals and minerals", also known as the "Mexican treasure"), a study made possible thanks to the network established by Cesi with Naples and Spain.[25] An important "lynx" and correspondent to Galileo was the Neapolitan Fabio Colonna (1567-1640), who carried out experiments on the nature of fossils and proposed their organic origin in an appendix at the end of his *Ekphrasis* (Fig. 1), and in the essay *De glossopetris*, both of 1616. Colonna was the first to place fossils in a biological context,[26] a field in which he was well-versed.[27] He also understood the promotional importance of illustrating plants, animals and fossils, a task brilliantly achieved through the new technique of etching.[28] In the end his interpretation of fossils relied more on morphological similarities with modern animals, than on experimental evidence, and his published texts were tightly connected with the erudite tradition inherited from late Renaissance and earlier naturalists.[29] This confirmed that experimentalism of early Galile-

[19] T. Kuhn, ref. 4, p. 219. The telescope brought about the immediate and irreversible collapse of Ptolemaic astronomy: D. Wootton, ref. 8.

[20] R. Raphael, *Reading Galileo. Scribal technologies and the Two New Sciences*, Baltimore, Johns Hopkins University Press, **2017**, p. 190. In the last part of the twentieth century epistemologists and historians of science fought over the nature of the "scientific method", positioning Galileo at centerstage: "hardly any other icon of modern science has become as much a victim of his interpreters as Galileo," wrote Klaus Fischer ("Die Wissenschaftstheorie Galileis – oder: Contra Feyerabend", *Journal for General Philosophy of Science/Zeitschrift für allgemeine Wissenschaftstheorie*, **1992**, *23*, p. 165-197). Fischer opposed the opinion held by Paul Feyerabend (*Against method*, see ref. 5).

[21] S. Drake, *Discoveries and opinions of Galileo*, New York, Doubleday & Company, **1957**, pp. 237-8.

[22] A. C. Scott, Federico Cesi and his field studies on the origin of fossils between 1610 and 1630. *Endeavour*, **2001**, *25*, pp. 93-103. D. Freedberg, *The Eye of the Lynx. Galileo, his friends, and the beginnings of modern natural history*. University of Chicago Press, 2002, 513 p. On the debates following the 1604 supernova see also P. J. Boner, *Change and continuity in early modern cosmology*. Springer, Dordrecht, 2011, 181 p.

[23] Several other publications illustratated with images of magnified objects (order of magnification being within the range of twenty to one hundred times) followed in Rome and elsewhere in Europe, until the much better-known images in Robert Hooke's *Micrographia* of 1665: D. Freedberg, ref. 22, p. 222.

[24] S. De Renzi, "Medical competence, anatomy and the polity in seventeenth-century Rome", *Renaissance Studies*, **2007**, *21*, pp. 551-567. "The sixteenth-century expansion of higher education, the rediscovery and publication of ancient medical and philosophical texts, and the subsequent debates between 'lower' and 'learned' practitioners over who was the true inheritor of ancient traditions all led to the emergence of an institutional debate about the nature of, and relationship between, various natural philosophical disciplines, and a concomitant emphasis that natural knowledge should be derived from experience rather than apriorist reasoning. […] Since the learned physicians accused the practitioners of being base Empirics, the latter sought to turn the accusation into a positive by elevating the status of experiential knowledge": D. Levitin, ref. 15, pp. 234-235.

[25] *Mexican Treasure*. Library of Congress, Washington D.C., World Digital Library, https://www.wdl.org/en/item/19340/ (accessed 5 March 2021). See D. Freedberg, ref. 22.

[26] M. J. S. Rudwick, *The meaning of fossils. Episodes in the history of paleontology*, Chicago, University of Chicago Press, 2nd edition, 1976 [**1972**], pp. 1-48.

[27] A. Ottaviani, "Fra diluvio noaico e fuochi sotterranei. Note sulla fortuna sei-settecentesca di Fabio Colonna", *Giornale Critico della Filosofia Italiana*, **2020**, *13*, pp. 260-271.

[28] Rudwick, ref. 26; Freedberg, ref. 22.

[29] A. Ottaviani, "La natura senza inventario: aspetti della ricerca naturalistica del linceo Fabio Colonna", *Physis*, **1997**, *34*, pp. 31-70.

Figure 1. Engraving of fossils from Malta, interpreted as shark teeth ("*Melitenses linguae, charchariae dentes et lamiae*") in Fabio Colonna's *De purpura, aliisque testaceis rarioribus*, appendix to his *Ekphrasis* of 1616. Some fossils are portrayed within the encasing rock. Creative commons, public domain.

ans went hand in hand with the humanistic textual approach transmitted by the scholastic tradition.

The experience of the Lincei as devised by Cesi, who kept contacts with Galileo until Cesi's death in 1630, ended with the definitive edition of the *Mexican treasure* in 1651. A second academy, directly connected with Galileo's teaching, was founded 15 years after his death. This was called Accademia del Cimento, or "academy of experiment".

THE ACCADEMIA DEL CIMENTO

After the publication of Galileo's "Dialogue concerning the two chief world systems" in 1632, followed in 1633 by his public recantation of Copernicanism – imposed after trial and condemnation by the Roman Catholic inquisition – Galileo spent his last years in Florence, host of the Grand Duke Ferdinand II of Medici (1610-1670). Here he was visited and assisted by two of his disciples, the mathematicians Evangelista Torricelli (1608-1647) and Vincenzo Viviani (1622-1703).[30] After Galileo's and Torricelli's deaths, Viviani was among the most active to transmit to posterity Galileo's teachings, mainly by promoting a Galilean agenda through his participation in the Accademia del Cimento. This new Accademia congregated in Florence beginning in 1657 around Prince Leopold of Medici, brother of Grand Duke Ferdinand II. From its inception to about 1660, members pursued research on the physical world through experiments and observations, led by skilled mathematicians like Viviani himself and the Sicilian Giovanni Alfonso Borelli (1608-1679) and animated by the activity and publications of founding member Francesco Redi (1626–1697) and others, such as Carlo Dati (1619-1676). This activity took place in continuity with that of other leading savants in contact with the Medici court, such as Marcello Malpighi (1628-1694). In 1656 Malpighi had been appointed Professor of theoretical medicine at the University of Pisa, continuing his career in Bologna where in the early 1660s he pioneered the use of the microscope in the study of the human body.[31] In those same years he undertook a close collaboration on mechanical anatomy and physics (or "iatromachanics") with Borelli, perhaps the most gifted mathematician of the Cimento.[32] Malpighi, Prince Leopold and other academicians kept contact with learned societies that were flourishing at that time across Europe, so that the Italians were an integral part of that community of natural philosophers and humanists called the "Republic of Letters".[33]

Lorenzo Magalotti (1637-1712), secretary since 1660, compiled a collection of the Cimento experiments and published it in 1667 with the title *Saggi di natura-*

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30 J. L. Heilbron, *Galileo*. New York, Oxford University Press, **2010**, 508 p.

31 According to D. Wootton, "between 1661 and 1691 more was discovered in biology than in any other generation since the death of Aristotle". This interest for a new type of observation, fuelled by expectation of economic gains, motivating investors like the Medici, gradually waned: "In the seventeenth century, Descartes had promised that sound natural philosophy would lead to a new medicine that would enormously extend life expectancy; by the end of the century even French Cartesian doctors had reconciled themselves to traditional medicine:" D. Wootton, *Bad medicine: doctors doing harm since Hippocrates*, Oxford University Press, **2007**, 336 p.

32 M. Malpighi, *The Correspondance of Marcello Malpighi* (Ed.: H. B. Adelmann), Cornell University Press, Ithaca-London, **1975**, 1, pp. 318-319. See also L. Boschiero, "Introduction", in *Borelli's On the Movement of Animals. On the Force of Percussion* (Tr.: P. Maquet), Brill, Leiden, **1989**, p. i-xxi.

33 R. Rappaport, *When geologists were historians*, Cornell University Press, Ithaca and London, **1997**, 308 p.

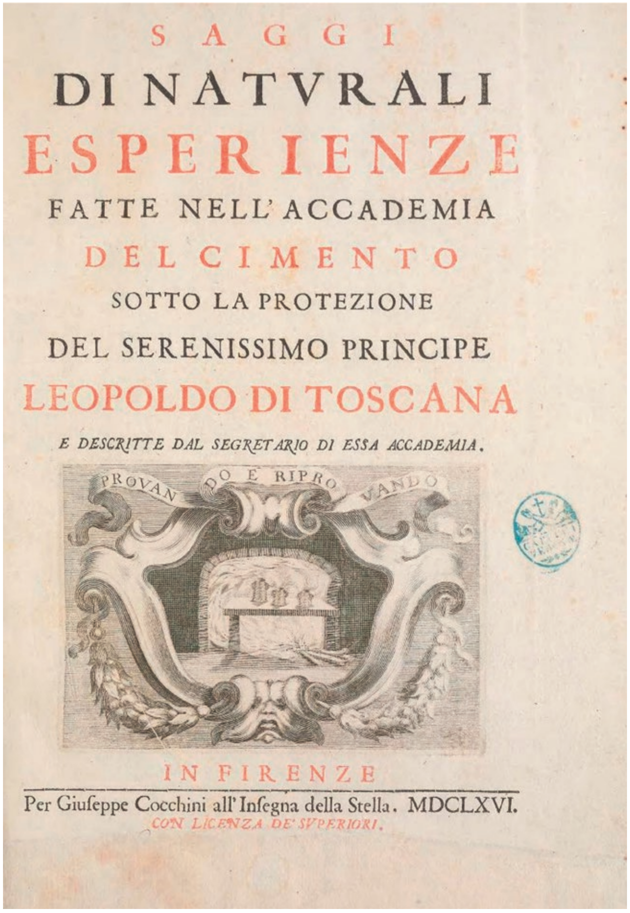
SAGGI
DI NATVRALI
ESPERIENZE
FATTE NELL' ACCADEMIA
DEL CIMENTO
SOTTO LA PROTEZIONE
DEL SERENISSIMO PRINCIPE
LEOPOLDO DI TOSCANA
E DESCRITTE DAL SEGRETARIO DI ESSA ACCADEMIA.
PROVANDO E RIPROVANDO
IN FIRENZE
Per Giuſeppe Cocchini all'Inſegna della Stella. MDCLXVI.
CON LICENZA DE' SVPERIORI.

Figure 2. Frontispiece of *Saggi di Naturali esperienze* by Lorenzo Magalotti and including the description of the experiments carried out in 1657-1660 at the Accademia del Cimento, in Florence. The book expressed part of the philosophical approach of disciples of Galileo at the Medici court. It was published in 1667, a few months after Steno's arrival there. Creative commons, public domain.

li esperienze (Fig. 2).[34] Probably to avoid controversies among members of the academy, Magalotti intentionally excluded debates about theory, giving the appearance of a non-speculative approach, at the same time boosting the idea that Galileo had started and transmitted a new method to the academy, one to produce atheoretical, factual knowledge of nature by experiments. Complex relations, different temperaments and rivalry between academicians have in part hindered the reconstruction of the philosophical debate taking place in Florence in 1657-1667. It is nevertheless clear that those debates testify to a fervent activity of research and of the ability of Prince Leopold to establish an environment where different approaches to natural philosophy could coexist.[35]

EUROPE AND THE NEW PHILOSOPHY

Galileo's writings influenced the work of three natural philosophers of the Scientific Revolution in France. The first was Marin Mersenne (1588-1648), who translated in French and promoted Galileo's Discourse one year after its publication and repeated some of the "experiences" of the Italian.[36] The second was René Descartes (1569-1640), who was marginally interested in Galilean writings and seemed more critical,[37] but nevertheless succinctly recognised in 1638 that Galileo's teaching was revolutionary because it abandoned "the errors of the schools and [brought] mathematics to bear on problems in physics".[38]

As did Galileo, Descartes rejected Aristotelian physics, and replaced it with a physics grounded in a mechanistic conception of nature, one that could be approached with mathematics. According to the French philosopher, the universe is made of void and of particles that can freely move by inertia, eventually colliding one with another. The fortune of Cartesian atomistic cosmology, circulating in the 1630s and published posthumously in Paris in 1664 with the title *Traité du monde et de la lumière*,[39] reached behind the evident flaws of the laws of inertial motion proposed by its author, and continued to inspire through the seventeenth century many aspects of natural philosophy. In astronomy it offered explanation to planetary motion, necessary for a self-consistent Copernican system. Johannes Kepler (1571-1630) had devised a mechanistic solar system

[34] L. Magalotti, *Saggi di naturali esperienze fatte nell'Accademia del Cimento sotto la protezione del Serenissimo Principe Leopoldo di Toscana e descritte dal segretario dell'Accademia*, Florence, Giuseppe Cocchini all'Insegna della Stella, **1667**, 286 p. Translated "Experiments in natural philosophy" in the fundamental study by W. E. K. Middleton, *The experimenters: a study of the Accademia del Cimento*, Baltimore, Johns Hopkins University Press, **1971**, 415 p. See also L. Boschiero, *Experiment and natural philosophy in seventeenth-century Tuscany. The history of the Accademia del Cimento*, Springer, Dordrecht, **2007**, 251 p., and M. Beretta, M. Feingold, P. Findlen, L. Boschiero, "Regress and rhetoric at the Tuscan court", *Metascience*, **2010**, *19*, pp. 187-210.

[35] P. Findlen, in M. Beretta, M. Feingold, P. Findlen, L. Boschiero, ref. 34, p. 204.

[36] R. Raphael, "Galileo's *Discorsi* and Mersenne's *Nouvelles pensées*: Mersenne as a reader of Galilean 'experience,' " *Nuncius*, **2008**, *23*, pp. 7-36. C. R. Palmerino, "Experiments, mathematics, physical causes: how Mersenne came to doubt the validity of Galileo's law of free fall," *Perspectives on Science*, **2010**, *18*, pp. 50-76.

[37] W. R. Shea, "Descartes as critic of Galileo", *New perspectives on Galileo* (Eds. R. E. Butts, J. C. Pitt), Dordrecht, Reidel, **1978**, pp. 139-159; R. Ariew, "Descartes as critic of Galileo's scientific methodology", *Synthese*, **1986**, *67*, pp. 77-90; R. Raphael, ref. 19.

[38] Letter to M. Mersenne of 11 October 1638, in R. Ariew, ref. 37, p. 81.

[39] R. Descartes, *Traité du monde et de la lumière*, Paris, Girard, 1664 [**1633**], 260 p.

governed by forces that move the planets around the sun. In the light of the concept of inertial motion introduced by Descartes, Kepler's system was amended by Borelli in 1666,[40] and separately, but simultaneously, by Robert Hooke (1635-1703) in England.[41] Finally, philosophy of knowledge, or epistemology, was at the core of Descartes' *Discours de la méthode* (1637), a brief but influential book about method in science.[42]

The third key figure of the new philosophy in France was Pierre Gassendi (1592-1655), an experimenter who also followed in the footsteps of Galileo.[43] Differently from Descartes, who in his *Principia philosophiae* of 1644 had proclaimed that there cannot be indivisible atoms, Gassendi proposed that primordial atoms may combine with one another to form larger and structured particles called "molecules". The French scenario developed until an institution similar to the Accademia del Cimento started in Paris, the Académie Royal des Sciences. This was formally founded in 1666, preceded by the work of informal academies that had been gathering there since 1661.[44]

The Gassendian approach was embraced in England by Robert Boyle (1627-1691), who brought the atomic and mechanical philosophies within the compass of experiment with the publication in 1661 of *Nova experimenta physico mechanica*.[45] One year earlier, Boyle had been one of the founding members of the Royal Society of London, the British analogue of the Florentine institution which, on matters concerning experimental philosophy, inherited the teachings of Francis Bacon and of the Oxford school.[46] Boyle adopted a "vitalistic corpuscularianism" and the experiments proposed by the iatrochemist Daniel Sennert (1572-1637) and the alchemical atomist Jan Baptist van Helmont (1580-1644).[47] The new practice of studying the inner nature of matter and its transformations was then called "chymistry". In the Dutch Republic, perfected microscopes were opening a window into the minutest parts of nature such as insects, showing "the wonders of God in the humblest creatures". New observations were influential during the 1660s, driving the transformation of museums "from collections of curiosities to cabinets of *naturalia*."[48]

In conclusion, during the years of activity of the Accademia del Cimento (1657-1667), when Steno received his formal education and made some of his most influential discoveries, an impressive series of pan-European events was shaping natural philosophy in an unprecedented way. The new "experimental philosophy", as it was also called then in England,[49] did not however break abruptly with the traditional approach, but remained in many ways connected with the humanistic tradition of reading ancient texts and interpreting them in the light of the new approaches to the study of nature.[50]

A particular case related to the quintessential book, the Bible. If the works of Aristotle or other classics were rediscovered during the late Middle Ages and the Renaissance, biblical exegesis had been practised at the highest levels without interruption for two thousand years and taught in European universities for centuries. Theology, and biblical scolarship with it, at least in part adapted to the new philosophy of nature by a process of inclusion, so that the learned Anglican bishop Edward Stillingfleet (1635-1699) could write in 1662 that "the best way to cure the world of atheism is true philosophy, or a search into the natures of things; which the more deep and profound it is, the more impossible will it be found to explicate all the phenomena of nature by mere matter and motion."[51] The early modern period was however also a time when skepticism towards its literal interpretation grew.[52] Textual criticism came to be

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40 G. A. Borelli, *Theoricae mediceorum planetarum ex causis physicis deductae*, Florence, S.M.D., **1666**, 184 p.

41 T. Kuhn, ref. 4, p. 237-260.

42 D. Garber, *Descartes embodied. Reading Cartesian philosophy through Cartesian science*, Cambridge University Press, **2000**, 337 p.

43 R. Raphael, ref. 20.

44 N. Dew, *Orientalism in Louis XIV's France*, Oxford University Press, Oxford, **2009**, 301 p.

45 M. P. Banchetti Robino, *The chemical philosophy of Robert Boyle. Mechanicism, chymical atoms, and emergence*, New York, Oxford University Press, **2020**, 196 p.

46 R. Jr Frank, *Harvey and the Oxford physiologists: scientific ideas and social interaction*, Berkeley, University of California Press, **1980**, 368 p.; M. C. W. Hunter, *Establishing the new science: the experience of the early Royal Society*, Woodbridge, Boydell, **1989**, 382 p.; D. Levitin, ref. 15. For Bacon see also D. Jalobeanu, " "The marriage of physics with mathematics". Francis Bacon on measurement, mathematics, and the construction of a mathematical physics", in ref. 10, pp. 51-80.

47 M. P. Banchetti Robino, *The chemical philosophy of Robert Boyle. Mechanicism, chymical atoms, and emergence*, New York, Oxford University Press, 196 p.

48 E. Jorink, *Reading the book of nature in the Dutch golden age, 1575–1715*, Brill, Leiden, **2010**, 472 p.

49 A. E. Shapiro, "Newton's "Experimental Philosophy"," *Early Science and Medicine*, **2004**, *9*, pp. 185-217.

50 D. Levitin, ref. 15.

51 E. Stillingfleet, *Origines sacrae: or a rational account of the grounds of the Christian faith, as to the truth and divine authority of the scriptures, and the matters therein contained*, London, Mortlock, **1662**, p. 408. See also S. Hutton, "Science, philosophy, and atheism. Edward Stillingfleet's defence of religion", in *Skepticism and irreligion in the seventeenth and eighteenth centuries* (Eds. R. H. Popkin , A. J. Vanderjagt), Amsterdam, Brill, pp. 102-120.

52 For the role of these freethinkers in their cultural environments see R. H. Popkin, A. J. Vanderjagt, *Skepticism and irreligion in the seventeenth and eighteenth centuries*, Amsterdam, Brill, 374 p.; A. Hessayon, N. Keene, *Scripture and scolarship in early modern England*, Ashgate, Aldershot, Hampshire, **2006**, 255 p.; E. Jorink, " "Horrible and blasphemous": Isaac La Peyrère, Isaac Vossius and the emergence of radical

openly discussed across different Christian confessions, such as in the work of the Protestants Isaac La Peyrère (1596-1676) and Isaac Vossius (1616-1689), the Anglican Francis Lodwick (1616-1694) and the Catholic Richard Simon (1638-1712). The most influential critic was the Jewish philosopher Baruch Spinoza (1632-1677), who adopted a form of natural religion in his *Ethica, ordine geometrico demonstrata* ("Ethics, demonstrated in geometrical order"), written between 1661 and 1675, a book that fuelled debate.[53] Notwithstanding the first burst of textual criticism of modernity, from Peyrère's "Praeadamites" of 1655 to Spinoza's "Ethics" of 1675, most seventeenth-century natural philosophers did not doubt that the first book of the Bible, the book of Genesis, was a reliable historical account of the distant past. Its understanding needed interpretation, the reason why a science of biblical chronology became a necessity, from the early works of 1642-1655 of John Lightfoot (1602-1675) and James Ussher (1581-1656), to that of Isaac Newton in the early eighteenth century.[54]

NICOLAUS STENO

At the age of 21 in 1659, while a student of anatomy at the Copenhagen Medical School, Steno kept a private journal in which he collected excerpts from, and wrote comments on, the books he and his teacher Ole Borch (1626-1690) read.[55] Titled "Chaos", this journal indicates that Steno's readings went beyond strictly medical matters needed in his university curriculum. He evidently aimed at an "understanding of the whole cosmos", to use Aristotles' words,[56] and not simply at becoming a court physician, or the Danish Royal Anatomist he later became.[57] Many of the excerpts relate to philosophical and methodological subjects. Regarding Galileo, Steno excerpted a passage from *Sidereus Nuncius* as it applied to a test for telescopes.[58] An interest in telescopes was coupled with a possibly greater fascination with microscopes, which, similarly to Galileo's telescope, posed the problem of sensory perception, whether the instruments revealed natural phenomena or artifacts of the technology. Steno wrote passages in his journal on the use of microscopes that related to different topics such as optic aberration, refraction, and geometric shapes seen in tiny crystals that appear round to the naked eye.[59] Regarding corpuscularism, he extensively excerpted the writings of Pierre Gassendi and Ole Borch, and used the word *corpuscula* ("tiny particles") 43 times in his journal, seeking to explain through atomistic theory disparate phenomena such as light, magnetism, colour, senses, changes in state, and the chemical behaviour of different solids and fluids.[60] This research reached its climax in 1666-1668, when corpuscular theory had became an integral part of the Florentine writings,[61] the word *corpuscula* being meanwhile substituted by *particulas* (repeated 36 times in the 78 pages of *De solido*). Sennert's *Institutionum medicinae libri V* was a book that in 1659 he read with enthusiasm and excerpted only on medical matters, but where he would have learned about an influential look on atomism in chemistry.

Descartes had brought method to centerstage. Steno widely read and excerpted the French philosopher, declaring in 1659 that he was willing to work "more accurately and orderly following Descartes' method."[62] In the first year of his stay in Florence he publicly praised Descartes' lesson in the use of mathematics as a means to true knowledge: "whoever thinks that its true understanding can be sought without mathematical assistance must also think that there is matter without extension, and body without figure."[63] In Florence he

biblical criticism in the Dutch Republic," in *Nature and Scripture in the Abrahamic religions: up to 1700* (Eds. J. M. van der Meer, S. Mandelbrote), Brill, Leiden, **2016**, pp. 429-450.

[53] R. Rappaport in ref. 33, p. 76. Criticism towards historicity of the biblical narrative was discussed only privately, and in small circles: see an eloquent example in W. Poole, "The Genesis narrative in the circle of Robert Hooke and Francis Lodwick", in *Scripture and Scolarship in Early Modern England* (Eds. A. Hessayon, N. Keene), Ashgate, Aldershot, Hampshire, **2006**, pp. 41-56.

[54] M. J. S. Rudwick, *Earth's deep history*. Chicago University Press, Chicago, **2014**, pp. 9-30.

[55] A. Ziggelaar, "Niels Stensen's Chaos-manuscript Copenhagen, 1659. Complete edition with introduction, notes and commentary", *Acta Hist. Sci. Nat. Med.*, **1997**, *44*, p. 301-302.

[56] Aristotle, ref. 1.

[57] G. Scherz, "Biography of Nicolaus Steno", in ref. 2 (Kardel, Maquet), pp. 6-346.

[58] A. Ziggelaar, in ref. 55, pp. 301-302.

[59] The journal of 1659 contains five passages on microscopes: A. Ziggelaar, in ref. 55, p. 290, 292, 296, 395, 396.

[60] A. Ziggelaar, in ref. 55. "*Clavis chymiae verae desideratur,*" Steno wrote, meaning "the key of true chemistry is wanted": p. 127).

[61] A. Clericuzio, "Meccanicismo ed empirismo nell'opera di Steensen", in *Scienza, filosofia e religione nell'opera di Niels Steensen* (Eds.: M. A. Vitoria, F. J. Insa Gómez), Pagnini, Firenze, p. 123-138.

[62] A. Ziggelaar, in ref. 55, p. 123.

[63] N. Stensen, *Elementorum myologiae specimen, seu musculi descriptio geometrica*, in T. Kardel, P. Maquet, ref. 3, p. 547, and references therein. See also S. Olden-Jørgensen, "Nicholas Steno and René Descartes: a cartesian perspective on Steno's scientific development," in *The Revolution in geology from the Renaissance to the Enlightenment* (Ed. G. D. Rosenberg), *Geol. Soc. Am. Mem.*, **2009**, *203*, 149-157. Olden-Jørgensen sees all of Steno's works as "operated within a securely Cartesian world" (p. 155). Application of the Cartesian method of doubt led Steno to experiment with new hypotheses in anatomy and new methods of dissection: V. Grigoropoulou, "Steno's critique of Descartes and Louis de La Forge's response," in *Steno and the philosophers* (Eds. R. Andrault, M. Lærke), Brill, Leiden, **2018**, p. 113-137. A critical view on Steno's cartesianism, and his debts to Pierre Gassendi and Francis Bacon, is found in A. Clericuzio, ref. 61.

interacted with some of the most learned mathematicians of his time, including perhaps the two most notable Galileans Vivani and Borelli. This he did in coincidence with the publication of the ultimate work on the activities of the Accademia del Cimento, the *Saggi di naturali esperienze* (Fig. 2).[64] Scholars are of the opinion that Steno was influenced by the Florentine method, particularly in *De solido*, by the deliberate adoption of "experience" as advocated in the *Saggi* as *historia*. Through the narration of experiments, *historia* was a form of empirism that focused on experience and challenged the scholastic approach of Aristotelian speculations about philosophical causes.[65] At the same time Steno distanced himself from the inductivist attitude expressed in the *Saggi*[66] by remaining a natural philosopher, interested in causal investigation.[67]

A SCIENCE FOR THE EARTH

The main subject matter of *De solido*, earth materials, such as strata, minerals and fossils, served as an attempt to establish a general method in the study of nature and a scale-independent means to disclose chronology of events in earth's history. The interest in *fossilia*, or *res metallica* (meaning anything dug up from the earth), had been emerging during the late Renaissance within the wider realm of natural history. Natural history was the job of keepers of museums, whether private such as that of Ferrante Imperato (1525-1615), or attached to public institutions, such as that of the Vatican *Metallotheca* in Rome, kept by Michele Mercati (1541-1593), and that of the Gallery of the University of Pisa, first organised by Andrea Cesalpino (1524-1603).[68] In the late 1650s and early 1660s, a number of phenomena relating to *fossilia* were attracting the attention of natural philosophers, as they had a few years earlier attracted Fabio Colonna in Rome (Fig. 1). Steno's elder competitors in this field were Athanasius Kircher (1602-1680) in Italy, Pierre Borel (1620-1671) in France, Ole Borch in Denmark and Robert Boyle (1627-1691) in England. In Florence, the young Dane proposed the first coherent and modern solution to explain the origin of fossils together with that of the strata that enclosed them. Anticipated by the publication of *Canis carchariae dissectum caput*, hastely written and published in 1667 (Fig. 3), his theory was briefly, but completely exposed in *De Solido*, published in 1669.[69] Both essays had immediate feedback in Europe.

The early modern period had become a time of travels in the explicit search of historical evidences of natural events. Noteworthy European travellers who interacted with Steno and who published essays on fossils (although the relationship among their travels and the study of fossils is not always clear), were his teacher in Copenhagen Thomas Bartholin (1616-1680)[70] and the early Fellows of the Royal Society of London, John Ray (1627-1705), Martin Lister (1638-1712) and Robert Hooke.[71] Philosophy of nature in the widest sense was at stake, not simply the explanation for the existence of "figured stones" or sports of nature. Common destinations for such travels were Montpellier, Sicily and Malta, where fossils are dug up in abundance to the present day. Agostino Scilla (1624-1700), another contemporaneous contributor to the debate on the origin of fossils,[72] could study them in his homeland, Sicily, a richly fossiliferous region. Steno, after travelling to Montpellier,

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[64] L. Magalotti, ref. 26.

[65] J. Bek-Thomsen, From flesh to fossils – Nicolaus Steno's anatomy of the Earth, in *A history of geology and medicine* (Eds.: C. J. Duffin, R. T. J. Moody, C. Gardner-Thorpe). *Geological Society of London, Special Publications*, **2013**, *375*, 17 p.; J. Bek-Thomsen, *Steno's* historia*: methods and practices at the court of Ferdinando II*, in ref. 13 (Andrault, Lærke), p. 233-258.

[66] P. Findlen, Controlling the experiment: rhetoric, court patronage and the experimental method of Francesco Redi, *History of Science*, **1993**, *31*, p. 35–64; L. Boschiero, *Experiment and natural philosophy in seventeenth-century Tuscany. The history of the Accademia del Cimento*, Springer, Dordrecht, **2007**, 251 p. Borelli, who contributed his thoughts to the *Saggi*, was particularly concerned to present the work of the Accademia as the accumulation of knowledge through rigorous experimenting, free of any theorising (Boschiero, p. 185). Inductivism is the view that science proceeds via generalization from facts recorded in basic sentences: J. Preston, *Feyerabend, philosophy, science and society*. Cambridge, Polity press, 234 p.

[67] "Steno was not writing as an anatomist or court physician but as a natural philosopher:" J. Bek-Thomsen, ref. 15b, p. 251.

[68] L. Tongiorgi Tomasi, *Giardino dei semplici. L'orto botanico di Pisa dal XVI al XX secolo* (Eds.: F. Garbi, L. Tongiorgi Tomasi, A. Tosi), Pacini, Ospedaletto, **1986**, pp. 161-170; M. J. S. Rudwick, ref. 26; P. Findlen, *Possessing Nature: museums, collecting and scientific culture in early modern Italy* University of California Press, Berkeley, **1994**, 449 p.

[69] T. Yamada, *Hooke–Steno relations reconsidered: reassessing the roles of Ole Borch and Robert Boyle*, in G. D. Rosenberg, ref. 7, p. 107-126. M. Romano, " 'The vain speculation disillusioned by the sense': the Italian painter Agostino Scilla (1629–1700), called 'The Discoloured', and the correct interpretation of fossils as 'lithified organisms' that once lived in the sea," *Historical Biology: An International Journal of Paleobiology*, **2014**, *26*, p. 631-651.

[70] G. Scherz, *Niels Stensen eine Biographie*, **1987**, translated in ref. 2 (Kardel, Maquet), p. 7-346. A. Ottaviani, "*Officiosissimam salutem nomine meo nunciabis Cl. viro Mario Schipano parentis amico veteri, quem laetus humanis adhuc interesse accepi, utinam diu*": memorie di viaggio e viaggio nella memoria nel tour italiano di Thomas Bartholin. *Schede umanistiche: rivista semestrale dell'Archivio Umanistico Rinascimentale Bolognese*, 2, **2004**, pp. 89-110.

[71] M. J. S. Rudwick, ref. 54, p. 49-100.

[72] Although never mentioning him, Scilla had surely heard about Steno's works through John Ray and Giovanni Alfonso Borelli: see P. Findlen, ref. 68.

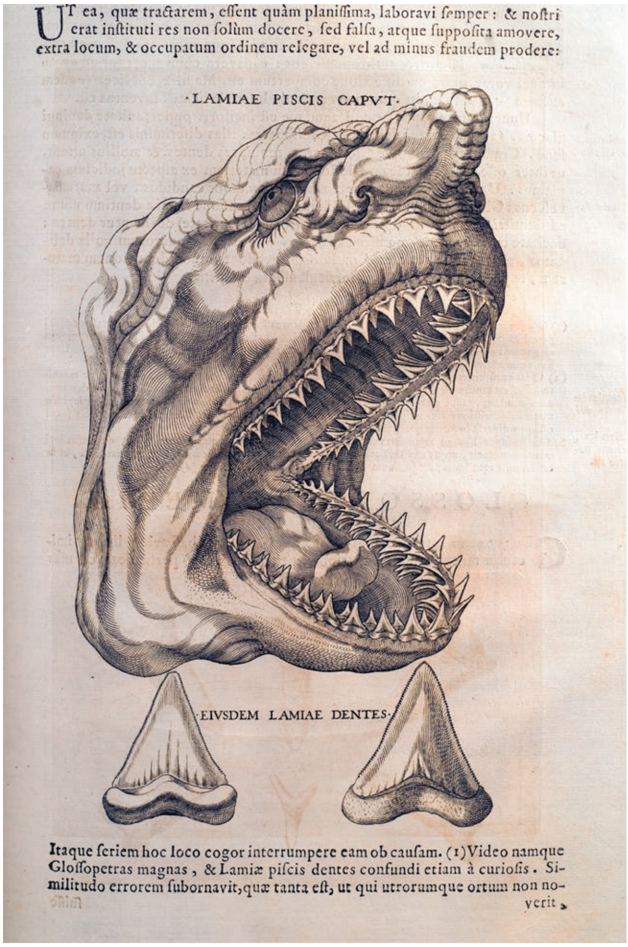

Figure 3. Portrait of a shark's head by Anton Eisenhoit (1553-1603), originally engraved around 1590 for Michele Mercati's *Metallotheca Vaticana* (published postumously in 1717) and used by Steno in 1666 to illustrate his *Canis carchariae dissectum caput*. Photograph by Saulo Bambi, reproduced with permission from *Metallotheca Vaticana*, courtesy of the Botanical Library of the Florence University.

had found in Tuscany the perfect place to immediately set out to work and study the natural setting where fossils were found, finally merging history of the earth with animal anatomy and corpuscular theory.[73]

By the time Steno's two "geological" works were translated and published by the Royal Society of London, in 1671, his primary interest in natural philosophy was waning, gradually substituted by the study of theology, seen as superior to the first as a way to truth (he became priest in 1675). Nevertheless, by combining the laws of physics and geometry with historical process and biblical scolarship, he had inaugurated a fruitful period in the study of the earth. This fluorished in the publication of a series of other theories, particularly among philosophers of the Royal Society, each one proposing his own take on merging natural history with the reports of human witnesses, centered in the book of Genesis and the tale of the universal deluge. The sheer number of theories of the earth published in 1669-1695, from those by John Ray, Martin Lister and Robert Hooke, to those of Thomas Burnet (1635-1715) and John Woodward (1665-1728), together with the fantasies of their constructs, gained their authors the title of "world makers".[74] By the time Steno died, in 1686 the focus of many learned men around him had gradually changed, no longer emphasizing mathematics as the language of the universe, but speculating on earth's history so as to merge physics with the biblical narrative. "Theory of the earth", or geotheory, became a genre, cultivated through the eighteenth century throughout Europe and culminated in the work of Louis Buffon (1704-1788), with his world-famous *Les époques de la nature* (1778). When Jean-Baptiste Lamarck (1744-1829) in France published his own geotheory in 1802 with the title *Hydrogélogie*, the genre had gone out of fashion among savants. Younger researchers had learned to start off from scratch once again. This they did by avoiding speculations and concentrating on the reconstruction of historical facts through the analysis of stratal relationships and the punctiform record of fossil occurrences of their own region. The leading figures of this new science, performed with hammer in hand in field activities and by study of museum collections, were Georges Cuvier (1769-1832) and Alexandre Brongniart (1770-1847) in France, Giambattista Brocchi (1772-1726) in Italy, and George Bellas Greenough (1778-1855) and William Buckland (1784-1856) in England. What they were doing was being called "geology" for the first time.[75]

THE THEMATIC VOLUME

For participants to the 2019 gathering, the Museum of Natural History of the University of Florence, hosting some of Steno's geological specimens, and the region of Tuscany itself, formed the perfect location to discuss the phenomena that Steno had observed from 1666-1668, the motivations for his research, the methodology of his discovery and, generally stated, the European scientific context which informed his inquiry. Some of the talks given in that meeting are included within this volume, kindly hosted by *Substantia*, International Journal of the History of Chemistry published by the Florence University

[73] A. Clericuzio, ref. 61.

[74] M. J. S. Rudwick, ref. 26, p. 49-100; R. Rappaport, ref. 33.
[75] M. S. J. Rudwick, ref. 54.

Press. In addition some of the invited speakers who were unable to attend, also contributed a paper to this publication. The collection is about earth science in the early modern period, when the study of minerals, rocks, and the fossilized remains of living things did not yet form a distinct path to knowledge about earth history, but was an integral part of the wider "philosophy of nature".

Participants to the thematic volume came from different parts of the world and from different backgrounds. Some are historians of science, others are physicians and geologists, with an experience in either medicine, mineralogy, paleontology or geochronology. Each understood from a particular point of view what observation, the experimental method, and use of geometry meant to early modern natural philosophers active in Italy, whether interested in the study of muscles, fossils, crystals or sedimentary strata.

Their papers in this volume contribute to understanding Nicolaus Steno's natural philosophy in the context of 17th century Europe. They reveal Steno and his contemporaries' interest in structure, origins, processes, and history of earth materials and fossil remains in a way that constitutes a glimpse into early attempts to understand natural history as we now understand it, even as many early conceptions of that story retained remnants of biblical and Aristotelian ideas. Stated a bit differently, the ideas in this volume bear on understanding the beginnings of the science of natural history, or evolution, as it is understood today.

Nicolaus Steno was a Galilean in the company of other Galileans, natural philosophers who largely shunned traditional scholastic speculations and valued instead observation and use of mathematics to describe nature and reveal its mysteries. The identification and description of scientific detail of the objects of nature – rocks, stones, fossils, animals, and plants – which is a recurrent theme in the volume – are pre requisites for understanding their evolution.

Alessandro Ottaviani's tour de force study of primary sources details the status of theories in the 17th century for the origin of stones and fossils (which then were anything dug up from the earth). Fabio Colonna did, however, predate Steno in recognizing that fossils are the remains of once-living things, but he invoked an Aristotelian model of material causes (water and earth) and efficient causes (heat and cold) for the origin of stones. Other natural philosophers, such as Federico Cesi, and Francesco Stelluti had advocated origin of fossils by various Aristotelian vegetal or plastic forces. And Cesi went further and adopted the idea of the continuum of divine creation, the Great Chain of Being, a classification scheme in which angels occupied a position closest to divinity followed successively by humans, animals, plants, and finally stones, any one of which could undergo degeneration, moving it farther away from divinity.

Nuno Castel-Branco examines the rapidly changing and vigorously debated epistemological role of mathematics in the 17th century as it applied to early modern medicine and particularly to Steno's accomplishments in anatomy. He shows how Steno used mathematics to reveal the structure of muscle and to show that glandular activity involved "humours," that is fluids, in a way that advanced the scientific understanding of the structure of the human body beyond the Cartesian model which oversimplified it as a machine. This approach by numbers in the study of the animal body, is argued, preceded Steno's first arrival in Italy.

Troels Kardel relates that Steno used mathematics to describe anatomical structures at microscopic scales not easily studied given the state of the instrumentation at the time, and so to leave him to hypothesize the existence of various anatomical transformations, among them, as Kardel has previously reported, and which he reinforces here, Steno's geometrical model whereby muscles contract by fiber shortening, not by a change in volume induced by animal spirits as was commonly speculated in the 17th century. Kardel emphasizes that Steno's mathematically inspired insight led him to propose time-related changes in organic and inorganic materials – even some that were too fast and others too slow to be observed by any individual. Yet many, including Steno's model of fiber shortening, were confirmed centuries later. In short, Steno used the predictive potential of geometric modeling to position himself on the verge of understanding time-related physiological changes in the human body.

Steno's embrace of Galilean methodology also facilitated his ascertainment of the founding principles of modern stratigraphy (what we now call original horizontality, superposition, and lateral continuity of sedimentary strata), paleontology (fossils are the remains of once-living things), and crystallography (constancy of interfacial angles in crystals, and anisotropic variations in crystal growth from accretion rather than by vegetative growth from within) – long before they became formal sciences.

Steno was of course neither always the first nor the only one to transition to modernity, but his steadfast Galilean natural philosophy elevated him to prominence. Silvio Menchetti states that Steno was the first to formulate constancy of interfacial angles of crystals, specifically for quartz and implicitly for hematite, but that he did not generalize his observations sufficiently to constitute expression of the universal law of interfacial angles. Menchetti believes that distinction belongs to later and more comprehensive studies by Romé de l'Isle (1736-1790). However, Menchetti asserts that Steno's discussion of crystal growth provides a more secure claim to his fame. That is, although Steno carefully considered Aristotelian causes in formation of crystals: material, formal, efficient, and final, he nevertheless concluded that crystals do not grow vegetatively from within, but by accretion of deposits from external fluids. Furthermore, Steno correctly theorized that crystal faces grow anisotropically (at various rates, accounting for different sizes and shapes of similar faces in different specimens, while maintaining constancy of interfacial angles).

Stefano Dominici's study indicates that Steno also studied fossil and modern shells and bones given to him by Giovanni Alfonso Borelli of the Accademia del Cimento and that he knew about Tuscan fossiliferous localities from reading of late Renaissance authors. Dominici proposes that Steno had planned geological fieldwork in Tuscany and that his geological works aimed also at attesting the veridicity of the biblical narrative. In that view, Steno's observations on fossils and strata did not start after the dissection of a shark's head, as it is generally assumed. For Steno the processes of transport and accumulation of sediments were consistent with the separation of the Aristotelian elements, earth and water, on the third day of creation according to Scriptures. Similarly, his recognition that "glossopetrae" were not simulacra of shark teeth molded by Aristotelian vital forces within the earth but were actually the dental remains of sharks that once lived in the waters of the Deluge, the second universal sea of Scriptures. Steno regarded the flood as scientifically consistent with the "freedom and powers" of the "First Mover," the divinity. Steno's description of the structure of Tuscan sedimentary strata involved relative age dating (organizing events in sequence), but he also tackled duration of that history (what is now called "absolute time"), albeit consistent with the 5,000-year age of the earth as described in Scriptures.

Alan Cutler's paper finds the beginnings of the modern rock cycle in Steno's study of Tuscan strata. Although neither Steno nor any of his contemporaries understood igneous or metamorphic processes, Steno nevertheless understood the role of erosion, transport, and deposition in the production of rocks that we now classify as sedimentary. Thus, Steno began the generative classification of rocks, or classification of rocks by method of origin, in this case the derivation of rock from pre-existing earth materials and thus the cyclicity of the earth processes that we now accept today. Cutler points out that such generative classifications are unique to geology. Specifically, Steno explicitly stated that structural characteristics of rocks and fossils reveal their place and mode of origin. Although Steno accepted that these cyclic processes started after the "malediction of earth" due to the curse of Adam, Cutler presents evidence that Steno was onto not only a modern understanding of relative time (e.g., his principles of molding and sufficient similarity as well as superposition, original horizontality and lateral continuity), but also a clear understanding that the duration of earth processes varies from instantaneous to prolonged (now known as "deep time"). In Steno's case the biblical narrative of 5,000 years since the creation framed his conception of deep time. Cutler's point is that Steno nevertheless understood time as a scale-independent concept in a way that is critical to modern geoscience and distinctive of it, in this example that the rock cycle has no set time frame. All of this is integral to our modern understanding of earth history: short-term and inconspicuous processes, instantaneous catastrophic events, and slow changes which take place over eons all play a role in earth history.

Desmond Moser finds a fundamental analogy in Steno's *Prodromus* between microstructural surfaces in crystals and surfaces of sedimentary strata and that Steno's recognition of it was "implicit in the *Prodromus* but not always recognized." His interpretation gives a coherence to Steno's diagrams in the *Prodromus* of crystals, some showing surfaces constituting zonation, and sedimentary strata showing layering. Moser tabulates Steno's references to chemical as well as structural micro- and megascopic layerings in various materials that Steno recognized were useful in establishing time-series (historical) sequences of formation – relative geochronology that is scale invariant in respect of both space and time.

Moser asserts that Steno's presentation amounts to a "revolutionary perception of scale invariance among the processes of solid formation in nature." Further, Steno's "observational acuity" combined with the "provenance of his [Galilean] philosophy" facilitated his recognition of geologic history which continues to be fundamental and evident to the present day in both relative (sequential) and absolute (durational) geochronologies at scales ranging from microcrystalline to regional geographic and on to planetary levels. Moser quotes Steno in saying, "*…these representations respond to a sign as if the macrocosmos laid hidden in the microcosmos*," manifestation of a long philosophical history in which the human body has been regarded as a model for "the animate earth."

The result is a collection of papers on the cultural environment that Steno found in Italy and on his previous experiences, how he innovated the discourse on minerals and fossils, and the geometric, scale-independent approach that stemmed from his published works, one that continues to be taught at universities around the world. The historical interval embraced by the different contributions spans from the early seventeenth century in Rome, at the Accademia dei Lincei, includes an extensive discussion of Steno's science while in Florence, and ends at our time on Mars, where Steno's geometric, visual approach to reconstruct historical processes proves to be basic for planetary science. In short, the papers in this volume establish that Nicolaus Steno had a more foundational insight into the modern concept of natural history than heretofore recognized.

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The Opposite Poles of a Debate - *Lapides figurati* and the Accademia dei Lincei[1]

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Abstract. The essay analyses the research carried out by some members of the Accademia dei Lincei on *lapides figurati*, namely by Fabio Colonna on animal fossils, and by Federico Cesi and Francesco Stelluti on plant fossils; the aim is to show the role played by the Accademia dei Lincei in establishing during the second half of the seventeenth century the opposite poles of the debate on the *lapides figurati*, on the one hand as chronological indices of a past world and, on the other, as sudden outcome of the *vis vegetativa.*

Keywords: Accademia dei Lincei, Fabio Colonna, Federico Cesi, Francesco Stelluti, Fossils, *lapides figurati*, *Rationes seminales.*

1. FABIO COLONNA ON FOSSILS

The research of Fabio Colonna (1567-1640) is fairly well known among historians of science, particularly in the fields of geology and palaeontology.[2] Given the links with Niels Steensen (1638-1686) and Agostino Scilla (1629-1700), these researches have concentrated on the 1616 dissertation on *glossopetrae*,[3] at the expense of several interesting observations already ventilated in 1606. The latter deserve analysis because Colonna there sets out the convictions at which he had already arrived on the basis of his initial inquiries, and which were to nourish the more accurate analyses contained ten years later in the dissertation. This early stage is represented in the long

[1] English translation by Peter Mason.

[2] On Colonna and 'palaeontological' themes cf. N. Morello, "Fabio Colonna e gli inizi della paleontologia", *Physis*, 1977, 19: 247-278; Ead., *La nascita della paleontologia nel seicento: Colonna, Stenone e Scilla*, Milano, Franco Angeli, 1979; A. Ottaviani, O. Trabucco, Theatrum naturae. *La ricerca naturalistica tra erudizione e nuova scienza nell'Italia del primo Seicento*, Napoli, La Città del Sole, 2007; A. Ottaviani, "*Methodus philologica* e *naturales quaestiones* fra l'Accademia dei Lincei e Galileo Galilei" *Galilaeana. Studies in Renaissance and Early Modern Science*, 2017, 14, 2017: 39-59; Id., "Fra diluvio noaico e fuochi sotterranei. Note sulla fortuna sei-settecentesca di Fabio Colonna" *Giornale critico della filosofia italiana*, 2017, 96: 272-303.

[3] Cf F. Colonna, *De glossopetris dissertatio*, in Id., *Purpura. Hoc est de purpura ab animali testaceo fusa, e hoc ipso animali, aliisque rarioribus testaceis quibusdam…*, Romae, Apud Jacobum Mascardum, 1616, pp. 31-39.

twenty-first chapter of the *Observationes*, included as an appendix in the *Ekphrasis* published in Rome by Guglielmo Facciotti. The opening of the chapter may confuse the reader: after a series of observations on cartilaginous fish, gastropods, marine invertebrates, mammals, reptiles and insects, Colonna unexpectedly introduces the bare outline of a theory on the origin of stones. Without preamble, in a style reminiscent of the *De lapidibus* of Theophrastus, Colonna concisely indicates the material causes (water and earth) and efficient causes (heat and cold),[4] and the effect of their various combinations. However, he continues, there are denser and purer concretions materially caused by those vapours that are drawn upwards by heat before freezing immediately in the atmosphere.[5] Colonna compares the process to an experience familiar to all: the concretions of the solfatara of Pozzuoli, which are obtained in a similar way in chemical laboratories,[6] or the stony incrustations produced by fumes. They seem to support the hypothesis that stones have a generic vegetal nature, and that their increase in size should be understood as a genuine process of growth.[7] Yet that would be a hasty conclusion, Colonna goes on to explain, because the increase in size of a stone can come about by the mere successive accumulation of parts according to two different modalities: augmentation from an external source or from the matrix of the stone.[8] The former resembles the way that shells grow through the hardening of the secretion that the animal periodically deposits on the edge of the shell; the latter is like the way in which nails and teeth grow from their matrix.[9]

There is no need here to follow the successive observations. In each case the focus is confined to the data observed, rendering virtually impossible any hypothesis on Colonna's sources. We know, however, that he owed his training to frequent direct contact with the recognised expert apothecary Ferrante Imperato (1550-1631). In 1599 Imperato had published the results of his researches, a large part of which was dedicated to the study of soils, metals, stones and gems. He offered several modalities for their genesis, some of them corresponding to those indicated by Colonna.[10] Master and pupil were not in complete agreement, however: Ferrante Imperato discussed not only the successive augmentation but also the truly vegetal property of stones,[11] a thesis from which, as we have seen, Colonna

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[4] F. Colonna, *De Aquatilibus aliisque animalibus quibusdam libellus* in Id., *Minus cognitarum Stirpium ac etiam rariorum nostro coelo orientium stirpium Ἔκφρασις*..., Romae, apud Guilielmum Facciottum, 1606, p. XLIII: «Adeo duo haec elementa cohaerent, terra scilicet et aqua, ut ex eorum quotidiana ad invicem commixtione maxime lapides generari perpetuo pro certo compertum habeamus. Nec alia est lapidis concretio, nisi terrae pars tenuior et purior aquae commixta, vel impurior aut terrestrior aqua, a solis calore exucta humiditatis parte ac etiam ab ambiente terra coire incipiens, frigore densata reliqua, sicciore deinde utrisque concurrentibus longo tempore intercedente in totum soliditatis naturam adepta, cum antea terreus liquor, vel aqueus lentus ac glutinosus esset. Terra quidem solis calore concocta aquis madefacta lentescit, nec minus quam arte effecta calx vel gypsum aqua mixtum liquescit ac facile coit, et exucta aquae parte, ab illa ignea natura per coctionem acquisita, reliqua ab extranea solis et frigoris vi exiccata, lapidis naturam adipiscitur. Densior vero, durior, aut fragilior lapis erit, si purior vel impurior, tenuior vel crassior terra immutata erit, magis vel minus solis ardoribus excocta, et deinde maioribus, vel minoribus frigoribus densata, longiore tempore perfecta».

[5] Ivi, p. XLIV: «Est et alia densior puriorque lapidum concretio, quae non ab ipsa terra vel aqua ad invicem imbribus commixtis efficitur ut superior, sed ab eorum vaporibus sursum elatis atque densatis, ut sunt lapides e caelo cum fulgure decidentes, durissimi atque politi».

[6] *Ibidem*: «Verum, ut exemplum afferamus quod oculis subiici et ex eo coniici possit modus elevationis vaporis et congelationis, proponemus sulphureas evaporationes Puteolanas,quae nobis aqueae videntur, attamen circa saxa specus e quo exeunt, sulphur adhaeret salis modo concretum, sed et ipsum artificiale sulphur: ex terra lapidibus calore vaporantibus, veluti per alembicum ex fornace fluit humor, qui sulphur est, sic et alia mineralia».

[7] *Ibidem*: «Sed et fuligo in caminis nonne, praeter illam spongiosam aut lanosam, in superficie alia subest crustosa dura? Et nihil aliud est nisi lignorum humiditas, tamen terream adeo magnam secum habet naturam, ac etiam lentorem quendam, ut in ligneis caminis observatur veluti pice infectis splendida vitrea crusta intectis fumo illam efferente. Ex huiuscemodi vero concretione facta lapides quidem vegetabilem quandam naturam habere conspiciuntur atque crescere illos quis putare posset».

[8] *Ibidem*: «Verum augmentum lapidi venit additione superveniente, ambiente vel, ut in his, ab imo succurrente, quare, veluti ab radice, alimentum et augmentum habere videtur».

[9] *Ibidem*: «Exemplum in dentibus et unguibus. De his quae per additionem crescunt, ut in testaceis maritimis et terrestris cochleis, quibus non centrum, sed circumferentia ampliatur. Signa rugarum testantur hoc ipsaque extremitas orae veluti cartilaginea, duritiem adhuc non habens, ex ambiente humore viscido ipsius animalis generata».

[10] F. Imperato, *Dell'Historia naturale*..., Napoli, per Costantino Vitale, 1599, p. 587: «Vien dunque in considerazione se le gemme da principio si apprendano nella propria grandezza come gli parpuglioni si concreano dentro delle lor cruste chiamate da alcuni aurelia, o se pigliano aumento da piccolo principio, come le creature crescono nel ventre materno e le foglie e i frutti nelle piante, o se crescono per semplice aggiunte fatte dalle radici come il capello e l'ungia, percioche si vede ciascuna delle dette manier haver propri argomenti [...]»; on Imperato cf. B. Accordi, "Ferrante Imperato (Napoli 1550-1625) e il suo contributo alla storia della geologia", *Geologica Romana* 1981, 20: 43-56; E. Stendardo, *Ferrante Imperato. Collezionismo e studio della natura a Napoli tra Cinque e Seicento*, Napoli, Accademia Pontaniana, 2001.

[11] Ivi, pp. 460-61, 659, 689: «E se noi consideriamo il modo del movimento et il corso delle fibre che dalle radici della marchesite si distendono, vederemo manifestamente in esse la virtù vegetale non dissimile a gli altri vegetali [...]. Dall'historia del Lyncurio più che da alcuna altra delle pietre narrate possiamo argomentare la virtù vegetale nella natura delle pietre qual molti hanno negato come cosa da quelle aliena; ma che la vegetazione che propriamente intendiamo essere l'accrescimento da principio interno non sia da questo geno aliena, possiamo riconoscere nelle parti dell'istessi animali percioche le corteccie degli animali marini che sono nel geno ostracino e non meno delle chiocciole terrene sono manifestamente di consistenza di pietra e si cuociono in calce non altrimenti che le pietre [...]. E si ha della sua vegetazione [del marmo] argomento molto evidente, percioche si sono ritrovate le cave già prima fatte nel successo di tempo rinchiuse dall'accrescimento della pietra».

was to distance himself. This is the move that provides the implicit but decisive characterisation of the lithological framework that he uses to introduce the real subject of the chapter: the description of the substantial series of fossils found. This commences with an interesting note on changes in the process of lithification depending on environmental conditions. In this context Colonna isolates two fundamental poles, that typical of arid, torrid zones, and that to be found in the cold, snowy and humid conditions of mountainous areas.[12] Colonna concentrates on the former, adducing a series of observations conducted in the environs of the small town of Andria in Apulia. Inspection of this hilly terrain with its tuff slopes revealed, surprisingly, a large number of shells stuck together in a perfect state of preservation that permeated the entire area.[13] As for the mountainous habitat, Colonna made observations during his frequent journeys over the Apennines, leading him to conclude that the fossils resulting from the process of putrefaction induced by humidity were of a very different kind, in which the lithic component had replaced the initial structure. Colonna was aware that it was cases like this that had led to the thesis of chance formation (*lusus naturae*), but the analysis of the structure, inserted within a temporal framework that Colonna vaguely defines as immemorial, suggests that they are the result of a slow decomposition of the organic remains and their successive lithification in parallel with the gradual transformation of the soil into a lithic state.[14] Colonna found confirmation of this in the exact correspondence of the *delineatio* of those forms transformed into stone to living creatures (see Figs. 1 and 2). Since that correspondence was not generic but specific, it could not be the result of a fortuitous generation.[15]

Colonna continues with a series of descriptions of fossils, accurately drawing from them those analyses of comparative morphology required to distinguish clearly between figured stones and fossils. Although he applied this morphological criterion with great precision – in this respect he was perhaps unequalled in his own day and only later by Steensen and Martin Lister – it had a weakness that he rapidly recognised. While Ferrante Imperato admitted the vegetal property, this was not incompatible with an explanation of fossil formation in terms of successive lithification. His son Francesco Imperato (1570 ca.- post 1629) adopted a solution that was equally possible and more linear: in an *opusculum* published in 1610, he did not rule out the possibility that the fossils found in the mountains might have been transported there by the flood, but this could only be applicable to those scattered on the surface; for those buried more deeply it was necessary to appeal to the action of a vegetal faculty. He emphasised the potency of this faculty, whose mimetic property rendered morphological similarities far less conclusive: 'So it is necessary to admit that it originates within the earth and then that it originates not fortuitously, but by an intrinsic vegetal capacity, while retaining the aspect of its counterparts'.[16] The *vegetabilis facultas* also applied to the *glossopetrae*, contrary to those who ascribed their origin to the teeth of sharks. Imperato considered that explanation impossible because of the quantity of *glossopetrae* found, which

[12] Colonna, *De aquatilibus aliisque animalibus quibusdam libellus*, p. XLV: «In montibus nivosis quidem ob continuam humoris abundantiam aquarum et nivium terra magis excolatur et colligitur in alveis in quibus deinde densatur atque ob humoris frequentiam ligna, cornua, animalium ungues, dentes, ossa, testacea crustacea e similia putrefiunt, quamquam a frigore servari possent, quod minime evenit in locis calidioribus et maritimis ut observavimus. Nam ibi ob humoris paucitatem et nimiam siccitatem potius servantur veluti condita ab aëre et humore tuta, quae ibi obruta inveniuntur».

[13] Ivi, pp. XLV-XLVI: «Et ut experientia comprobari hoc videatur, nostram in hoc observationem afferemus, quam omnes veram fateri oportebit. Apuliae tractus in quo civitas nobilis est *Andria* dicta, tota collibus et clivis referta tophaceis, quibus ad aedificiorum ornamenta et structuras arte elaboratis utuntur, et per totam fere Apuliam etiam similibus. Quibus conspectis, nihil aliud quispiam esse dixerit, quam acervum sive potius massam testaceorum maritimorum terreno glutine confectam, atque varia cochlearum conchyliorum testaceorumque fragmenta ac etiam integra observabis nullam corruptionem adhuc temporis passa. Nec in quolibet communi manuali lapide duo aut tria conspicies, sed totum ex illo confectum dices, ut vix altera fit terrae portio. Nec etiam uni lapidi hoc accidere, sed toto colli, nec uni sed omnibus per totam illam regionem».

[14] Ivi, p. XLVI: «Non autem hoc ita in Apenninis montibus evenit, ut diximus, rebus humorem adversantibus et in terram putrescentibus. Nam et ipsas maritimorum animalium testas putrescere ibi certum est, sicut ligna, ossa et terrestres etiam cocleas et alia de quibus dicemus. Quae omnia non integra et veluti servata, sed penitus putrefacta in lapidem versa vel potium saxum, ut ad siliceam naturam parum accedere videantur ob duritiem, densitatem et levorem, cum illa in Apulia servari videantur a tophacea concretione fragili admodum respecta saxorum. Huius rei contemplationis causa fuerunt varia testacea aliaque naturalia intra saxorum moles inventa eadem saxorum natura, sed propria effigie servata. In quorum structura animadvertendum censuimus, illa non sic intra saxa naturam efformasse fortuito, ut aliqui putant, sed immemorabili tempore ab hominibus deiectis et casu terra obrutis, intra humum putrescentibus, illa sicut ambiens terra in lapidem deinde mutata elementorum perpetua vicissitudine, non minus ac excussores ac sculptores faciunt ex convexa cavam effigiem atque e contra convexam».

[15] *Ibidem*: «Hoc testari videtur exacta admodum illorum delineatio atque cum ipsis naturalibus similitudo atque etiam copiosa eiusdem rei, eiusdem effigiei magnitudinis et structurae inventio. Non enim, si casu an natura effingerentur, tam similes et exacte formarentur ut eadem prorsus res, non dicimus species, videatur».

[16] Cf. Fr. Imperato, *De fossilibus opusculum*..., Neapoli, Typis Jo. Dominici Roncalioli, 1610, p. 69: «Unde opus est fateri intra terram ortum ducere et successive, non casualiter, sed vegetabili facultate iniuncta originem ducere similium servata effigie»; on this *opusculum* see Fr. Imperato, *De fossilibus opusculum (1610)*, (Eds.: F. Brattolo, F. Coletta, M. Pladini, C. Pisaniello, C. Porcaro, E. Stendardo), Napoli, Accademia Pontaniana, 2015.

Figures 1 & 2. Two plates from Colonna, *De Aquatilibus aliisque animalibus quibusdam libellus* (1606), representing shells of fossil and living animals. The fossil *specimens* are: Fig. 1. *Pectunculus lapideus* (upper left corner); *Concha lapidea recurva* and *Concha lapidea Nautili effigie* (both on the second line from the bottom); *Concha lapidea gibbosa* (lower left corner); Fig. 2. *Buccinum lapideum laeve* (upper left corner). Colonna claims to have found them in the environs of Andria, in Puglia, and in the fortress of Campochiaro, in Molise. The other represented specimens are all from living animals.

he regarded as incompatible with the number of sharks to have populated the seas since the beginning of the world (though he does not reveal the basis of his calculations): 'Indeed, on the island of Malta we discover every day tooth-shaped stones, which are (mistakenly) taken to be the teeth of sharks; because they are extracted in such numbers all over the island that they exceed the number of teeth of all the cetaceans that ever lived from the origin of the world down to the present day'.[17]

Colonna's response to this implicit polemic was to concentrate on the *glossopetrae*, conducting not only the usual morphological comparisons but also subjecting them to chemical analysis. He regarded the different products obtained from combustion of the fossil part and the lithic part as proof that the matrix and the tooth had different origins. It was an ingenious but inconclusive attempt, since the *glossopetrae* were derived from a 'warm' environment. The results obtained from lithic fossils extracted from mountainous and snow-covered terrains might be very different – an objection that was often raised in the subsequent debate.[18]

[17] Ivi, pp. 69-70: «Equidem in Melita Insula quotidie cernimus lapides quosdam dentium formas exprimentes, qui lamiarum dentes putantur (sed falso); nam ex qualibet dictae Insulae parte adeo copiose eliciuntur, ut nec omnium cetorum dentes, qui ab origine mundi usque num vitam duxere, illorum numerum aequare possint».

[18] At least down to the beginning of the following century, for which cf. E. Camerarius, *Dissertationes Taurinenses epistolicae physico-medicae*…, Tubingae, Impensis Joh. Georgii Cottae, 1712, pp. 268-279, which reports on the chemical analyses by Guillaume Rivière: cf. J. Gaudant. "Une nouvelle contestation de la nature organique des fossiles: les *Dissertationes taurinenses Epistolicae physico-medicae* d'Elias Camerarius (1712) *Travaux du Comité français d'Histoire de la Géologie*, s. III, 2012, 26: 235-240.

2. CESI AND STELLUTI ON METALLOPHYTES

In the years intervening between 1606 and 1616 Fabio Colonna was admitted to the Accademia dei Lincei. The *De glossopetris dissertatio* was an independent work, but became attached to the malacological treatise *De purpura*. The two works were then combined with the botanical work entitled *Minus cognitarum stirpium Pars altera* published in Rome by Giacomo Mascardi,[19] underlining the ascription to the Lincei. It was during the preparation of the *Thesaurus Mexicanus* that the Neapolitan, who was by now involved with the Roman associates, first came into contact with Prince Federico Cesi's researches on *lapides figurati*. The occasion was the dispatch of a proof of the first pages of the *Tabulae phytosophicae* that Federico Cesi (1585-1630) planned to include among the commentaries contained in the volume. In a letter of 10 November 1628 to Francesco Stelluti (1577-1653), who was acting as intermediary, Colonna gave his first impression from Naples after a hasty perusal of the tables: 'The first sheet, the table of the whole *Thesaurus* and the principle of division or rather distinction, gave me great pleasure. I am certain that the ingenuity of Your Excellency is such that I hope it will command universal admiration when parts of these things appear in print'.[20] Though time was pressing, Colonna commented on some links in Cesi's remarkable chain and formulated some possible diagnoses of them. One of these concerned the *zoolithophyton*, the other the *Pianta Metallo*, which he thought might be identified with Ferrante Imperato's marcasite (*argento ramoso*).[21]

In the latter case Colonna was wide of the mark, but in a certain sense he was correct in assuming that the answer should be sought among the treasures of the apothecary. After all, Cesi had visited Imperato in 1604 in the course of his trip to Naples and had observed there, as Francesco Stelluti recalled in 1630, a cytisus (a genus of plant) and some pieces of fossil ebony.[22] Colonna was not in Naples on that occasion, but we may suppose that, even when he was, he would not have retrospectively recalled that mineralised ebony, which Ferrante Imperato explained simply as the remains of fossil wood.[23] The extant documentation shows that Cesi must have discovered his *Pianta Metallo* in the first decade,[24] but there is little information about that until the beginning of the second decade, when Cesi had already decided to make his contribution to the *Thesaurus* in the form of tables and to confer a strategic role on the so-called intermediate natures in order to illustrate effectively the *continuum* of the divine creation. He wrote to Johann Faber (1574-1629) asking for information regarding 'whether anyone has distinguished and listed fossils in an orderly fashion in their classes, particularly the metallic ones and semi-minerals; and likewise whether anyone has summarised the sciences synoptically in tree structures and tables'.[25]

We do not have Faber's reply, nor can we reconstruct the reading and researches leading to 1624, the year in which Johann Baptist Winther (? – 1628 ca.), writing to Faber on 18 May, mentions a double excursion with Cesi in the course of which he drew the prince's attention to a 'certain point' in the *De metallicis libri tres* by Andrea Cesalpino (1519-1603); Cesi declared that it coincided with his own opinion.[26] The passage in question is part of the forty-first chapter of the second book in the section on *gemmae pellucidae*. It is introduced by a premise intended to make it clear that the chapter will deal only with fossil ebony and not black coral. Cesalpino knows that many authorities take them to be related, if not identical, but the only thing in common that he is prepared to concede is their colour. Otherwise

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[19] Cf. F. Colonna, *Minus cognitarum stirpium par altera*…, Romae, Apud Iacobum Mascardum, 1616.

[20] G. Gabrieli, *Il Carteggio Linceo*, Roma, Accademia Nazionale dei Lincei, 1996, p. 1187.

[21] Ivi, pp. 1187-88: «Io non so per dire il vero che cosa sia la pianta animale lapidea, sotto il nome di *zoolithophyton*, che desidero sapere come cosa da me finhora non osservata, credo per non l'haver havuto: così anco la *Pianta Metallo*, se pur sia differente dall'argento ramoso descritto dall'Imperato»; for the reference to marcasite see above, note 10.

[22] Cesi describes the journey in a letter to Stelluti dated 17 July 1604 in ivi, pp. 40-41; cf. also F. Stelluti, *Persio tradotto in verso sciolto e dichiarato*, Roma, appresso Giacomo Mascardo, 1630, pp. 169-170: «Mi ricordo bene che in Napoli il Signor Ferrante Imperato Autore di un Museo così ricco e celebre, mostrò al nostro Signor Principe Cesi […] una spezie di Citiso, come parve ad esso Signore, quale si potrà vedere, e qualche de gli Ebani minerali dice da esso scoperti, ne suoi libri de Metallofiti, che presto doveranno stamparsi»; Stelluti was anticipated by Faber in his commentary in the *Thesaurus Mexicanus*, already printed in 1628, in which he reported Cesi's discovery without going into the merit of the thesis regarding its origin: see *Rerum medicarum novae Hispaniae thesaurus seu plantarum, animalium, mineralium Mexicanorum historia*…, Romae, Ex Typographeio Vitalis Mascardi, 1651, pp. 502-503.

[23] F. Imperato, *Dell'Historia naturale*, op. cit. pp. 668-669; the same opinion in Fr. Imperato, *Discorsi intorno a diverse cose naturali*, Napoli, Nella Stamperia di Eg. Longo, 1628, pp. 3-4.

[24] A.C. Scott, "Federico Cesi and his field studies on the origin of fossils between 1610 and 1630", *Endeavour*, 2001, 25(3): 93-103; also useful G. Godard, "Les travaux géologiques de la première *Accademia dei Lincei* (1603-1651)", *Travaux de comité français d'histoire de la géologie*, 2011, s. III, 75(5): 119-137.

[25] Gabrieli, *Il carteggio linceo*, p. 732.

[26] Ivi, p. 881: «Siano stati due volte in luogo montuoso et argilloso, dove si trovano certi sodissimi legni in gran quantità, negre et odorate, con bellissime vene sotto terra, stimati dal Sig.r Principe Minerali, sonno bene grandi argomenti del sito e della sostanza d'alcuni di loro petrificata. Io, havendo letto nel Cesalpino il capo del Ebano, ho trovato un certo punto, il quale mostrato al Sig.r Principe gli confermò totalmente la sua opinione, se bene non mancano argomenti in contrarium validissimi, tanto ch'io non so che dirmi sin'hora. Però mi mostro d'andare con i piedi ne la opinione del Sig.r Principe».

they originate in different environments – black and all other corals in the sea, fossil ebony on land – and their nature remains to be determined. If black coral is undeniably vegetal, the nature of fossil ebony is inscrutable; Cesalpino does not exclude the possibility that it is a root or wood that has been lithified, like coral, or that it is a stone that simply resembles wood.[27] The ambiguity went back to the ancient sources such as Pausanias, whom Cesalpino quotes. He reports the explanation of a Cypriot that ebony was a sort of subterranean vegetal lacking leaves and fruit: 'Ebony does not grow leaves or bear fruit, or even appear in the sunlight at all, but consists of underground roots which are dug up by the Ethiopians, who have men skilled at finding ebony'.[28] More recent discoveries, such as those made in the environs of the town of Hildesheim in Lower Saxony, reported at length by Giorgio Agricola (1494-1555) in his *De natura fossilium libri X*, failed to resolve the question either,[29] leaving open the possibility of arguing for a transformation from wood to stone, while leaving open two possible scenarios of the process: that of a slow transformation, projected into the past, and that of metamorphosis by lightning. But this ambivalence is common: we can find it for example in William Camden (1551-1623),[30] and equally in Cesalpino, who seems reluctant to come down in favour of either opinion.

It is regrettable that Winther did not specify the nature of that 'certain point' with which Cesi had expressed his agreement. But we do know what his frame of reference was at the end of the year, thanks to the only extant fragment from the materials that the prince was compiling to deal with the matter in depth. This document owes its origin to the desire to address a letter to Cardinal Francesco Barberini with a concise explanation to accompany the gift of a table made of ebony. The brief but dense letter is intended above all to underline the importance of this discovery in the eyes of the cardinal because of its capacity to increase knowledge of the so-called intermediate nature, otherwise defined as *entia imperfecta*. Although Cesi stresses the completely unparalleled way in which these metallophytes combine two or even three natures, he locates their essential characteristic in their bituminous nature. This is followed by a list of examples of *naturalia*: the stones *gagates* (jet) and *aetites* (eagle stones), on whose disputed identification Cesi concurs with Pliny;[31] another jet-like stone known as *acciavaccio* (the Neapolitan term for a dark stone known in Spanish as *azabache* and used as a talisman), fossil ebony, lithanthracite (these are simply named), and finally agalloch, aloe wood, whose

[27] A. Cesalpino, *De metallicis libri tres*…, Romae, Ex Typographia Aloysii Zannetti, 1596, Liber II, cap. XLI, pp. 126-127: «Ad gemmas non pellucidas reduci possunt corallii, rubrum, candidum, et nigrum, quod Antipathes dicitur. Egimus autem de iis inter plantas. Antipathi similis est Ebenus fossilis, sive radix sit, lignumve Ebeni in lapidem concreti, sive omnino lapis per se genitus ligno similis. Differt a Corallio nigro: hoc enim non nisi in mari nascitur; ebenus foditur»; Gabrieli, *Il carteggio linceo*, cit., p. 112, n. 3 assumes Winther was referring to A. Cesalpino, *De plantis libri XVI*, Florentiae, Apud Georgium Marescottum, 1583, Lib. 3, cap. XXXIIII, pp. 114-115, that contains, at any rate, the same opinion on the *Ebenus fossilis*.

[28] Pausanias, *Description of Greece with an English Translation by W.H.S. Jones*, London, William Heinemann-New York, G.P. Putnam's Sons, 1918, pp. 227, 229; followed by a reference to Theophrastus: see Cesalpino, *De metallicis libri tres*, p. 127: «Et Theophrastus tradit Ebenum fossilem inveniri inclusum aliis lapidibus tamquam foetum in ventre. Si igitur haec vera sunt, nec radix nec arbor dicenda est in lapidem conversa, sed lapis Ebeno similis in fibris Saxorum genitus». The passage, however, does not correspond to any of those in which Theophrastus discusses ebony.

[29] Cesalpino, *De metallicis libri tres*, p. 127: «Nec tamen absurdum etiam Ebeni lignum intra terram diu conditum lapidescere, quod & aliis generibus lignorum contigisse compertum est», followed by a reference to G. Agricola, *De natura fossilium libri X*, Basileae, In Officina Frobeniana, 1558, pp. 324-325: «In Hildesheimio quoque in terra aluminosa inventum est lignum quernum in lapidem conversum. In eodem e regione arcis Marieburgi collis est plenus lapideis trabibus, quarum capita interdum eminent. Sunt vero perlongae, acervatim positae, inque medio earum terra est, colore nigra, ferro aut altero lapido percussae non aliter nec marmor Hildesheimium, de quo supra dixi, cornu usti virus olent, omninoque ex eadem materia sunt, quare cum natura lapides arborum similes procreet, diligenter videndum est an corticem et medullam aliaque habeant. Quae si absunt non stipites in lapides conversi sunt, sed natura fecit lapides stirpium simillimos, quales sunt trabes istae Hildesheimiae. Trabs igitur quam Iovianus Pontanus invenit in promontorio Pausyllipi, cum tempestas artem monte abrupuisset, qualis fuerit, non possumus scire; non enim explicatur an fuerit saxum, quod trabs speciem prae se ferebat, an lignum in saxum conversum»; Cesi owned copies of the treatise of Cesalpino and of Agricola (in the edition of 1616): cf. M. T. Biagetti, *La biblioteca di Federico Cesi*, Roma, Bulzoni, 2008, p. 266, n° 151 for Cesalpino, and pp. 271-272, n° 2259 for Agricola.

[30] Agricola *De natura fossilium*, p. 325: «Iidem autem fontes et fluvii chirotecas et ossa aliasque res in se immissas, ut forma prior maneat, ossaque dissolvens cum corpore tabificus seps, in lapidem conversus nuer ad rivum quendam montis piriferi salso dicti inventus est»; W. Camden, *Britannia*…, Londini, Impensis, Georg. Bishop, 1600, *e.g.* p. 542: «Ubi flumen australem agri limitem attingit inter ericeta et iacentia loca, in quibus, uti etiam alibi, arbores ab inundato mundo, ut credunt, defossas saepe eruunt»; p. 622: «Sub quo fons est in quem ex impendentibus rupibus aquae guttatim distillant, unde *Dropping Well* vocant, in quem quicquid ligni immittitur, lapideo cortice brevi obduci et lapidescere observatum est».

[31] Cited from Gabrieli, *Il carteggio linceo*, p. 966: «Fra questi ho veduti i nascimenti del Gagate, ancorché lontano dal Gange, del Aetite ad esso prossimo; nel che venga lodato Plinio, e liberato dalla calunnia, che communemente se l'è data, d'haverli insieme congionti»; the reference is Pliny X 12. Cesi read *gagaten*, the accepted reading in the editions until then, while modern editors (*e.g.* Detlefsen, Mayhoff, Rackham, De Saint Denis, König and Winkler) accept the reading *gagiten*; the principal ancient sources on the stone were Dioscorides V 129 and Pliny XXXVI 141. The latter is not free of errors, on which cfr. A. Mottana, "Ricerche di iconografia mineralogica: *I.* La pietra «gagate» nel *Codex medicus graecus 1* della Biblioteca Nazionale Austriaca", *Rendiconti della Accademia dei Lincei. Classe di scienze fisiche, matematiche e naturali*, 2002, s. IX, 13: 89-112.

legendary origin in terrestrial paradise Cesi mentions in passing.[32] The list is intended to display the salient properties of the metallophyte,[33] comprised within the spectrum of characters extending between the extremes of jet, which Pliny describes as 'black, smooth, porous, light, not very different from wood, and brittle, and has an unpleasant smell when rubbed'[34] and of agalloch, noted for its fragrance.[35]

According to Francesco Stelluti, the detailed description of the *naturalia* in this list and their relation with metallophytes would have corresponded to the treatise on which Cesi was working.[36] Stelluti regretted that Cesi's early death had prevented him from completing it and saved the most valuable part – the woods of Acquasparta – from oblivion when he dedicated a brief *Trattato* to them in 1637. Stelluti presents his own thesis as the result of a laborious intellectual trajectory that involved the rejection of what he claimed as the most natural

Figure 3. Plate from Stelluti, *Trattato del legno fossile* (1637). The annotation runs: "This piece of wood, ovoid from A to B, was three palms high; I say high because it was found with the part A facing downwards and the part B facing upwards; and from C to D it was thirteen palms long; from E to F it was eleven palms long; from F to G ten and a half palms. From G to H the wood was covered with earth while it was being excavated, and it was impossible to see where it ended." Although the annotation does not mention it, the fragments represented on the upper left were presumably detached during the excavation.

hypothesis, viz. that they were the remains of trees buried a long time before that had slowly been transformed into stone.[37] The absence of roots, seeds and other circumstantial evidence led him ineluctably to the idea that they originated from 'a soil type containing a lot of chalk, which gradually converts it into wood' (see Fig. 3).

[32] Presumably Cesi took the legend from P.A Mattioli, *Commentarii secundo aucti in libros sex Pedacii Dioscoridis Anazarbei de materia medica*…, Venetiis, In officina Valgrisiana, 1560, p. 48: «Sunt qui somniantes dixerint Agallochi arborem vidisse neminem, cum terrestri tantum paradiso proveniat, illudque ferri fabulantur fluminibus quae (ut sacra testantur monumenta) ex eo manant. Atqui pro comperto habetur (ut paucis innuit Serapio) Gangem Indiae amplissimum fluvium quam plurima secum Agallochi fragmina vehere, quae tamen in ipsum ducuntur aliorum fluminum cursu, qui in eum confluunt. Quippe cum fluvii transluant loca, ubi Agallochum provenit, aquarum inundationibus turgentes, huius truncos, fragmina ac ramenta rapiunt una cum aliis varii generis lignis, et in Gangem transferunt, quemadmodum in nostris etiam fluminibus saepe ac saepius visitur. Cuius rei indicium affert illud quod Venetiis venditur, utpote quod longo aquarum discursu omni ex parte laceratum, exesum, comminutumque spectetur»; the primary source for the *agallochum* is Dioscorides I 22.

[33] A very forced interpretation of this list is proposed by D. Freedberg, *The Eye of the Lynx. Galileo, His Friends, and the Beginnings of Modern Natural History*, Chicago and London, The University of Chicago Press, 2002, pp. 327-328, though as a preliminary to an interpretation of Cesi's mineralogical researches on which serious doubts have been cast by P. Galluzzi, «*Libertà di filosofare* in naturalibus». *I mondi paralleli di Cesi e Galileo*, Roma, Scienze e Lettere, Accademia Nazionale dei Lincei, 2014, pp. 425-426 [= Idem, *The Lynx and the Telescope. The Parallel Worlds of Federico Cesi and Galileo*, trans. P. Mason, Brill, Leiden, 2017, pp. 382-383].

[34] Pliny, XXXVI, 142: «Niger est, planus, pumicosus, levis, non multum a ligno differens, fragilis, odore si teratur gravis».

[35] Confirmation that the list serves to define the spectrum of the qualities of the metallophyte can be found in Stelluti's statement that the sample can emit a distateful odour like that of gagate, or a more pleasing one closer to the extreme sweetness of the scent of aloe wood: F. Stelluti, *Trattato del legno fossile minerale nuovamente scoperto*…, In Roma Appresso Vitale Mascardi, 1637, p. 7: «Se si mette al fuoco mentr'è stato cavato di fresco dalla terra, s'abbrucia, ma lentamente con gran fumo, e con odore spiacevole. Quando poi il legno è secco, l'odore è più grato […]».

[36] Ivi, pp. 11-12: «[P]oiché non solo scriveva della generatione di dette pietre e legno, e delle pietre aquilini, che pure in detti luoghi se ne genera gran quantità, ma di tutte l'altre pietre note sin qui, e di altre ancora non più osservate, ne descritte da altri Autori».

[37] Ivi p. 6: «Ne meno si può credere, che questi legni siano tronchi o frusti d'alberi sotterrati in quei luoghi, o caduti, e dalla terra ricoperti, e formati poi con quell'onde da quell'acque minerali, che ivi scaturiscono, e da fuochi sotterranei, com'io nel principio mi persuasi, per haver trovato alcuni olmi ricoperti dalla terra in quei luoghi, dove detto legno si trova, perché la sua forma si varia, e la mole si grande mi fa credere il contrario, non trovandosi alberi mai dalla natura formati come nelle seguenti figure si vedrà […]»; on Stelluti cf. *Francesco Stelluti Linceo di Fabriano*, Fabriano, Città e comune di Fabriano, 1986.

It has been repeatedly claimed that such a thesis could not have appealed to Cesi because of its excessive naïveté, but apart from the fact that comparison of the letter to Barberini with the text of Stelluti does not afford any positive evidence for such a difference of opinion, there is a clue that enables us to qualify Stelluti's thesis as fully compatible with the philosophical horizon of Cesi enshrined in the *Tabulae Phytosophicae*. They show a clear adhesion to the Paracelsian doctrine of *transplantatio*. This doctrine allows that, given certain conditions, the process of changing along the axis of the natural *continuum* that usually proceeds downwards (commonly defined as *degeneratio*) can operate in the reverse direction and even perform considerable leaps.[38]

3. FROM THOMAS BARTHOLIN TO JOHANN JAKOB SCHEUCHZER

However eccentric and extreme the solution suggested by Cesi and Stelluti, it remains anchored to the vision of nature summed up in the action of *rationes seminales* or *spiritus metallicus*.[39] This vision was by no means marginal in the course of the seventeenth century, and often adopted in order to explain the origin of fossils and figured stones, from Johann de Laet's *De gemmis et lapidibus libri duo* (1647),[40] and Ulisse Aldrovandi's *Musaeum metallicum*, posthumously edited in 1648,[41] to the catalogue of Manfredo Settala's *Wunderkammer*.[42] This helps to understand why the *Trattato del legno fossile minerale* was, with a few very rare exceptions,[43] favorably received as, for example, by Fortunio Liceti (1577-1657), Martin Schoock (1614-1669), Charles Patin (1633-1693), and Athanasius Kircher (1602-1680).[44] More interesting is the case of the Danish physician Thomas Bartholin (1616-1680), who in 1643 went on a long Italian tour that took him to Rome, Naples, Sicily and Malta. In the course of his journey, he wrote that, in the course of planning a treatise on this material, he had arrived at a view of the *glossopetrae* that in no way agreed with that of Colonna.[45] At the same time as he rejected the conclusions of the latter's dissertation, Bartholin, who recorded having seen 'the spectacle of the new wood' in Rome, had no objection to the thesis of Stelluti.[46] Bartholin thereby gave form to a duality that was destined to be repeated, although two decades later Colonna's thesis seems to be widely acknowledged, for example by Johann Daniel Major (1634-1693) and Her-

[38] On this aspect cf. Ottaviani, "*Methodus philologica* e *naturales quaestiones*, op. cit.

[39] Obviously, this notion had a long history: see H. Hirai, *Le concept de semence dans les théories de la matière à la Renaissance: de Marsile Ficin à Pierre Gassendi*, Turnhout, Brepols, 2005, and A. Clericuzio, *Elements, Principles and Corpuscles. A Study of Atomism and Chemistry in the Seventeenth Century*, Dordrecht-Boston, Kluwer, 2000.

[40] See Johann de Laet, *De gemmis et lapidibus libri duo*…, Lugduni Batavaorum, Ex officina Ioannis Maire, 1647, p. 177: «Quemadmodum spiritus metallicus a Deo terrae natura inditus, in venis auri argentique mirabilia artificio efformat arbusculas et herbas, ex auro et argento, ita in lapidicinis etiam varias effigies testaceorum animantium e materia plane lapidea et quasi metallica, quod et supra vidimus in lapidibus serpentinis et cornua Ammonis. Quare meo iudicio frustra sunt qui opinantur has conchas aliquando testaceas fuisse et viva animantia continuisse et successi temporis in lapides esse conversas».

[41] Cf. U. Aldrovandi, *Musaeum Metallicum in libros IIII distributum*, Bononiae, Typis Io. Baptistae Ferronii 1648.

[42] Cf. *Museum Septalianum Manfredi Septalae patritii Mediolanensis industrioso labore constructum, Pauli Mariae Terzagi physici… descriptum…*, Dertonae, Typis Filiorum qd. Elisei Violae 1664; *Museo o Galeria adunata dal sapere e dallo studio del Sig. Canonico Manfedo Settala nobile milanese, descritto in Latino dal Sig. Dott. Fis. Paolo Maria Terzago et hora in Italiano dal Sig. Pietro Francesco Scarabelli Dott. Fis. di Voghera e dal medesimo accresciuta*, in Tortona, Per li Figliuoli del qd. Eliseo Viola 1666.

[43] G. Naudé, *Lettres inédites* écrites *d'Italie à Peiresc, 1632-1636*, *publiées et annotés par Philippe Tamizet de Larroque*, Paris, Léon Techener, 1887, pp. 42-43, 51-52.

[44] Cf. F. Liceti, *De tertio-quaesitis per epistolas clarorum virorum, medicinalia potissimum, et aliarum disciplinarum arcana postulantium responsa*…, Utini, Ex Typographia Nicolai Schiratti, 1646: *Liceti resp. De multiplici generatione Succini, Eboris, Ebeni et ligni, deque viribus Electri*, pp. 200-201; M. Schoock, *Tractatus de turffis ceu cespitibus bituminosis*…, Groningae, Typis Johannis Cöllenii, Bibliopolae et Typographi, 1658, pp. 72-74; C. Patin, *Traité des tourbes combustibles*…, A Paris, Chez Jean Du Bray, aux Espics-Meurs et Pierre Variquet. À l'Enseigne du Gril, 1663, p. 45; A. Kircher, *Mundus subterraneus in XII libros digestus*, Tomi 2, Amstelodami, Apud Joannem Janssonium et Elizeum Weyerstraten, 1664-5, especially II, p. 65 on Stelluti's treatise.

[45] T. Bartholin, *Epistolarum medicinalium a doctis vel ad doctos scriptarum centuria I et II*, Hafniae, Typis Matthiae Godiccheni, 1663: Centuria I. Epistola LIII. *De raris naturae in Insula Melita observatis*, pp. 223-224; Epistola LVI. *De Glossopetris Melitensibus*, p. 240: «Nam de Glossopetris optimum agnosco iudicium tuum, quae cur ex metallorum ordine exigendae sint, basin rationum parum firmam apud F. Columanm observo, de quibus incoram pluribus, si Deo visum est, agemus»; Epistola LVII. *De Glossopetris*, pp. 241-242.

[46] T. Bartholin, *De Unicornu observationes novae*…, Patavii, Typis Cribellianis, 1645, pp. 283-284: «Novi Ligni spectaculo ex terrea lapidi mixta materie saeculum nostrum illustravit nuper Natura duobus retro messibus, Aquaspartae in Umbria, ubi lignum fossile inventum cedro Mauritanico simile, venis in longitudinem extensis, non in altitudinem, quia radice caret, cortice interdum fragili, aliquando durissima et aspera partim lignea partim cretacea, sed medulla duriore. Mirum variantis naturae miraculum cum stupore apud unicum eius inter mortales authorem *Cassianum Puteum* vidi, et in rei fidem dono singulari aliquam eiusdem ligni partem rudem partim, partim tornatam, servo. Resinam lignorum instar sudat candidam mastichi similem vel thuri, metallique filamenta quaedam habet et capillamenta, ut nomen metallophyti impetravit a *Francisco Stelluti* qui totam eius historiam Etrusco idiomate cum depicto ligno typis Romae vulgavit, ubi et terram fossilis huius materiam inde exploravit quod gleba ei adhaerens humida post aliquot menses tota evaserit lignea, a calore, ut arbitror, temperato, quem modica oleosque humiditas in sicciorem lapidem vetat indurescere».

mann Conring (1606-1681),[47] and, with more substantial evidence, by Steensen in his *Canis Carchariae dissectum caput* (1667) and *Prodromus* (1669),[48] and Scilla, in his *La vana speculazione disingannata dal senso*, edited in 1670.[49]

In 1671 Paolo Boccone (1633-1704), when he was in Paris, published a series of observations in two modest volumes.[50] France was the first stage of the journey that he had reluctantly undertaken once it had become clear that he would be unable to remain in Tuscany, where he had found his niche as personal botanist to the Grand Duke. One of the two works was on the nature of fossils. Convinced like Colonna that they originated from plants and animals,[51] Boccone crossed the Alps in the knowledge that his thesis was finding confirmation by Steensen with whom he was on cordial terms. As it happened, 1671 was the year in which Steensen's theses were severely criticised by Martin Lister (1639-1712).[52] In a letter of 13 December 1673, Henry Oldenburg wrote to Lister:

> I have now in my custody a boxe, left with me by a Sicilian, Paulo Boccone, (an inquisitive person, especially as to Plants and Figured stones,) for the repository of the R. Society; in which, amongst other curiosities, there are several pieces of Coral, red and white, some hard and solid, others britle sticking about pieces of wood etc. which latter may much inform us about the original of coral, and teach us, that'tis of a stony, not vegetable nature.[53]

Boccone had hardly left England, the second stage of his journey, where he had made a favourable impression. He now headed for Holland, where he was to publish the Parisian works in a single volume in Amsterdam in 1674, taking into account the recent English and Dutch discoveries. He made no mention of Lister;[54] we do not know the reason for this silence, but it may be supposed that the Englishman's objections, which ended up reviving the 'plastic virtue' hypothesis, may have had a *déjà-vu* ring to Boccone. The abovementioned Scilla's treatise was ably promoted by Boccone; in that work Scilla replied point by point to the letter in which the Maltese physician Giovan Francesco Buonamici (1639-1680) opposed the Colonna/Steensen position, based on an elaborate version of the genesis of fossils and other figured stones by the action of occult seeds.[55]

The successive decades, however, had more than one surprise in store for Boccone. Both in England and on

[47] See J.D. Major, *Dissertatio epistolica de cancris et serpentibus petrefactis...*, Jenae, Typis Joannis Nisii, Sumptu Esaiae Fellgiebeli, Bibliop. Vratislav. 1664, and H. Conring, *De antiquissimo statu Helmestadii et viciniae coniecturae*, Helmestadii, Typis et impensis Henningi Mulleri, 1665, pp. 35-36: «Sunt scilicet talia dentes carchariae, aut lamiae, aliorumque cetaceorum marinorum. Quod praeclare docuit singulari dissertationi Fabius Columna, de Melitensibus eiusmodi glossopetris disputans».

[48] N. Steensen, *Canis Carchariae dissectum caput et dissectus piscis ex canum genere*, in Id., *Elementorum myologiae specimen…*, Florentiae, Ex typographia sub signo stellae, 1667; *De solido intra solidum naturaliter contento dissertationis prodromus…*, Florentiae, Ex typographia sub signo stellae, 1669.

[49] A. Scilla, *La vana speculazione disingannata dal senso. Lettera responsiva circa i corpi marini che petrificati si trovano in varii luoghi terrestri*, Napoli, Appresso Andrea Colicchia, 1670.

[50] P. Boccone, *Recherches et observations naturelles* and *Recherches et observations curieuses sur la nature du corail blanc et rouge, vray de Dioscoride*, both Paris, Chez Claude Barbin, 1671.

[51] On Boccone's research on fossils cf. B. Accordi, "Contributions to the History of Geological Sciences; Paolo Boccone (1633-1704) – A Practically Unknown Excellent Geo-paleontologist of the 17th Century", *Geologica Romana* 1975, 14: 353-359.

[52] M. Lister, "A Letter... written at York August 25 1671 confirming the Observation in N° 74 about Musk sented Insects; adding some notes upon D. Swammerdam's book of Insects, and on that of M. Steno concerning Petrify'd shells", *Philosophical Transactions*, 1671, 6: 2281-2285; on which cf. N. Morello, "Le «conchiglie stravaganti» da Colonna a Lister", in *Il Meridione e le scienze (secoli XVI-XIX)* (ed.: P. Nastasi) Palermo, Università di Palermo, Istituto Gramsci Siciliano di Palermo, Napoli, Istituto Italiano per gli Studi Filosofici, 1988, pp. 257-279; A.M. Roos, *Web of Nature: Martin Lister (1639-1712), the First Arachnologist*, Leiden-Boston, Brill, 2011.

[53] *The Correspondence of Dr. Martin Lister (1639-1712). Volume One: 1662-1677*, (ed.: Anna Marie Roos), Leiden-Boston, Brill, 2015, p. 639; Oldenburg is providing Lister with a synthesis of the content of the "Account of some of the Natural things, with which the Intelligent and Inquisitive Signor Paulo Boccone, of Sicily hath lately presented the Royal Society, and enriched their Repository" already published in *Philosophical Transactions*, 1673, 6158-6161.

[54] P. Boccone, *Recherches et Observations naturelles*…, Amsterdam, Chez Jean Jansson à Waesberge, 1674, where Lister is also passed over in silence, "A description of certain stones figured like plants, and by some observing men esteemed to be plants petrified…", *Philosophical Transactions* 1673, 8: 6181-6191, although he added considerable material on the astroite: ivi, cf. pp. 118-124, 135-149.

[55] Buonamici's letter was printed much later: cf. G.F. Buonamici, "Lettera missiva… diretta ad Agostino Scilla…. ove si tratta dell'origine delle glossopietre, occhi di serpi, bastoncini detti di san Paolo, ed altre pietre figurate, che si cavano dall'isola di Malta e del Gozzo", in *Opuscoli di Autori Siciliani*, Palermo, Per Pietro Bentivenga, 1770, vol. XI: 105-195, 188: «Né anco è da credere a mio parere, che solamente i semi occulti, e principi materiali di quell'animaletti minuti e stimati comunemente meno perfetti si contengono dispersi nell'acqua e nella terra, ma anco de' maggiori e più perfetti, sicché questi potrebbono similmente generarvisi, toltone però l'uomo, la di cui produzione non fu commessa alla terra, ma riserbata alla mano dell'Altissimo, come della più perfetta delle creature, ch'è composta di spirito e corpo, checché si sia sognata la pagana antichità e de' suoi Preadamiti abbia empiamente scherzato la Perriera moderno scrittore, de' suoi omicciuoli fatti per arte chimica entro una caraffa scrisse Paracelso, e di non so che razza d'uomini verdi scappati dal seno della terra lasciò registrato il Neobrigense»; Buonamici had already stated his position in a letter to Michele Giustiniani, published by the latter in *Lettere memorabili… parte prima*, Roma, Per Nicolò Angelo Tinassi, 1667, pp. 389-404; on him cf. N. Morello, "Giovanni Francesco Buonamico and the Fossils: A Flood of Problems", in *Italian Scientists in the Low Countries in the XVIIth and XVIIIth Centuries*, (ed. Cesare S .Maffioli – Lodewijk C. Palm), Amsterdam-Atlanta, GA, Rodopi, 1989, pp. 131-145.

the continent, the challenge of Lister and Buonamici was taken up in a sequel of interventions, which, irrespective of the arguments deployed to reject totally or to limit the validity of the theses of Colonna and Steensen, had in common a view holding that fossils originate by plastic virtue or occult seeds.[56] Quite eloquent was the case of the Swiss physician Johann Jakob Scheuchzer. Born at Zürich in 1672, graduated at the University of Utrecht, Schuechzer in 1697 published an essay entitled *De generatione conchitarum*.[57] Still far from wholeheartedly embracing the diluvian theory that he was soon to adopt after reading the works of John Woodward,[58] Scheuchzer treated this complex material warily, cautiously weighing up the two major theses in open conflict, and eventually (with many reservations) came down on the side of Steensen, whose works he read with great care.[59] Nevertheless, only a few years later Scheuchzer continued to appreciate that position but restricted its scope even further as he grew inclined to accept the arguments of those who clung firmly to *panspermia*, the *spiritus mundi* or the *archeus* espoused by van Helmont.[60] We do not know whether his change of attitude was also influenced by his turning attention to vegetal forms, but it is certain that, whether willingly or not, in the divergence resulting from the juxtaposition of the two *sententiae*, Scheuchzer ended up reproducing a polarity whose dialectical tension had been taken to its limit by the Accademia dei Lincei.

[56] That is the case of John Ray, Robert Plot Edward Lhwyd, Johann Jakob Wagner, Johann Jakob Reiskius, Theodor Geyer, Elias Camerarius, Karl Nikolaus Lange, just to cite a few.

[57] J.J. Scheuchzer, "De generatione conchitarum", *Miscellanea curiosa sive Ephemeridum medico-physicarum Germanicarum Caesareo-Leopoldinae naturae curiosorum* 1697, 4, *Appendix*: 151-166, pp. 155 and 157: «Non etiam immorabor multum [...] descriptioni accuratiori figurae conchitarum [...] ut nec solutioni famosae illius apud litographos quaestionis, num sc. conchitae aliique lapides figurati fuerunt aliquando revera conchae, cochleae &c. fluviatiles vel marinae, atque adeo spolia diluvii universalis, inundationum particularium, absorbitionum terrae, quae postea in terra relicta a petrificante quodam succi il lapides transmutata vi, an non potius sint id genus lapides corpora terrigna, atque adeo mire variantes suas figuras terrae debeant, non mari; corporibus inanimatis, non incolis maris, animalibus variis. [...]»; e p. 157: «Non satisfacit mihi, si verum fateor, Reiskii vis κυγκχοποιητικὴ, Salmasii aptitudo huius vel illius loci peculiaris, ad continendum eiusmodi succum conchiferum, Geyeri succus lapidescens, et sal illud modificans Wagneri et aliorum vis seminalis terrae innata»; on him cf. M. Kempe, *Wissenschaft, Theologie, Aufklärung. Johann Jakob Scheuchzer (1672-1733) und die Sintfluttheorie*, Epfendorf, Bibliotheca Academica Verlag, 2003.

[58] The hesitations, still present in *Specimen lithographiae Helveticae curiosae*, Tiguri, Typis Davidis Gessneri, 1702, disappear from *Piscium Querelae et Vindiciae*, Tiguri, Sumtibus Authoris, Typis Gessnerianis 1708.

[59] Cf. Scheuchzer, "De generatione conchitarum", pp. 155 and 157: «Non etiam immorabor multum [...] descriptioni accuratiori figurae conchitarum [...] ut nec solutioni famosae illius apud litographos quaestionis, num sc. conchitae aliique lapides figurati fuerunt aliquando revera conchae, cochleae &c. fluviatiles vel marinae, atque adeo spolia diluvii universalis, inundationum particularium, absorbitionum terrae, quae postea in terra relicta a petrificante quodam succi il lapides transmutata vi, an non potius sint id genus lapides corpora terrigna, atque adeo mire variantes suas figuras terrae debeant, non mari; corporibus inanimatis, non incolis maris, animalibus variis. [...]»; e p. 157: «Non satisfacit mihi, si verum fateor, Reiskii vis κυγκχοποιητικὴ, Salmasii aptitudo huius vel illius loci peculiaris, ad continendum eiusmodi succum conchiferum, Geyeri succus lapidescens, et sal illud modificans Wagneri et aliorum vis seminalis terrae innata».

[60] Cf. J.J. Scheuchzer, "Dissertatio epistolica Acarnanis de Dendritis aliisque lapidibus, qui in superficie sua plantarum, foliorum, florum figuras exprimunt", *Miscellanea curiosa sive Ephemeridum medico-physicarum Germanicarum Caesareo-Leopoldinae naturae curiosorum*, 1700, 5-6, *Appendix*: 57-80, p. 67: «Sic non improbaverim eorum sententiam, qui Spiritui mundi, Archeo sive natura universali, in globum hunc terraqueum ubique panspermia imbutum perpetuo agenti, et pro subiecti diversitate figuras varias producenti cuncta tribuunt»; on van Helmont see W. Pagel, *Joan Baptista van Helmont: reformer of science and medicine*, Cambridhe [et alibi], Cambridge University Press, 1982.

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Dissecting with Numbers: Mathematics in Nicolaus Steno's Early Anatomical Writings, 1661-64

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Abstract. At the height of his scientific career, the anatomist Nicolaus Steno published the *Elementorum myologiæ specimen* (Florence, 1667), a book unlike any other anatomy book until then. Rather than an anatomy book, it seemed more like a book of mathematics, with propositions, lemmas and corollaries. Steno is thought to have developed his mathematical interests in Florence with the school of Galileo. However, this article challenges this interpretation and argues that Steno's turn towards mathematics was a gradual process that began earlier in Copenhagen and Leiden. By surveying Steno's early anatomical writings, mathematical methods such as quantification measurements, mechanical analogies, and geometrical models come to light. More importantly, these methods are read in their own context, by considering what mathematics really meant in the early modern period and how anatomists used it. As such, this article provides a more complete picture of Steno's interest in mathematics and it sheds new light on the rise of mathematics in the early modern life sciences.

Keywords: Nicolaus Steno, Early Modern Science, History of Anatomy, Mathematization, Mechanical Philosophy, Mixed Mathematics, Quantification, Dissection Culture.

INTRODUCTION

When the anatomist Nicolaus Steno arrived in Florence and published the *Elementorum myologiae specimen* (1667), he claimed that the study of the muscles had to become "part of mathematics" and that the cause of "many errors … in the description of the human body" was that "until now anatomy has disdained the laws of mathematics."[2] The book seemed more like a

[1] I would like to thank the editors Stefano Dominici and Gary Rosenberg, as well as the reviewers Peter Dear, Jeremy Gray and François Duchesneau for very helpful comments and suggestions. I also benefitted much from discussions with Troels Kardel and John Heng at the workshop "Galilean Foundations for a Solid Earth" in October 2019, in Florence. Finally, a special thanks to Evan Ragland and María Portuondo who kindly read and commented on an earlier version of this article.

[2] Nicolaus Steno, *Elementorum myologiae specimen* (Florence, 1667), p. iii-iv: "non posse in musculo distincte partes eius nominari, nec motum eiusdem considerari feliciter, nisi Matheseos pars

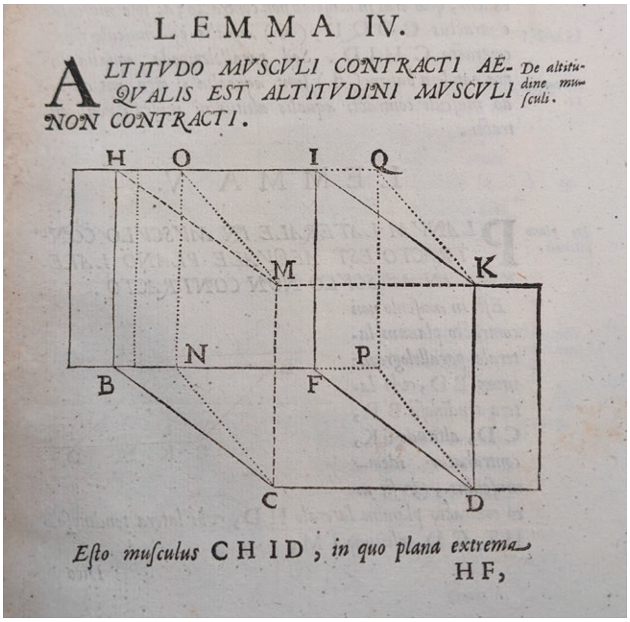

Figure 1. "Lemma IV: The height of a contracted muscle is equal to the height of the non-contracted muscle." Steno, *Elementorum myologiæ specimen*, p. 21; BOP, p. 667.

mathematics than an anatomy book, due to its propositions, lemmas and corollaries, and strong epistemological claims about the role of mathematics in the study of nature (fig. 1).[3] This mathematical approach was seen likewise in Steno's most famous work, also published in Florence, the *De solido intra solidum naturaliter contento* (1669), where he laid down the principles of superposition of the Earth's strata and in which he described the formation of crystals and of the Tuscan mountains by means of geometry.[4] Since Steno's earlier works did not display such an explicit use of mathematics, it may seem that he completely changed his research methods when he arrived in Florence. However, as this article argues, that was not the case.

Rather than a sudden shift, Steno's turn towards mathematics was a gradual process. Early in his anatomical career, Steno used methods directly associated with the early modern pure and mixed mathematics. The mixed mathematic disciplines, such as astronomy, mechanics or optics, used the methods of pure mathematics – arithmetic and geometry – to explain natural phenomena. Such methods included quantification measurements, geometrical models, and even the axiomatic structure of mathematical treatises.[5] Simple uses of quantification like counting did not necessarily entail an interest in mathematical methods, unless they were used to make stronger epistemological claims. Scholars who worked on mixed mathematics aimed to achieve higher levels of certainty in their description of the natural world.[6] For that reason, seventeenth-century mixed mathematics, later known as physico-mathematics, used not only mathematical methods but also new experimentation techniques and mechanical analogies to explain natural phenomena.[7] For example, historian Peter Dear explains that the book *Ars magnesia* (Würzburg, 1631) by the Jesuit Athanasius Kircher (1602-1680) was "a physico-mathematical disquisition" on magnetism where experimental accounts were presented in the form of theorems.[8] Steno carefully studied the second edition of this book as a university student in Copenhagen, including the chapters where Kircher illustrated magnetic attraction by means of hydrostatic devices.[9]

Besides outlining Steno's early uses of mathematics and mechanical analogies, this article shows that such uses derived in large part from his interest in mixed mathematics and not so much from the mechanical philosophies of his time.[10] Although Steno may be

Myologia fieret," and "innumerabilium errorum, quibus humani corporis historia fœdè inquinatur, quàm quod Matheseos leges Anatome hactenus indignata fuerit." For a full English translation see Troels Kardel and Paul Maquet, *Nicolaus Steno: Biography and Original Papers of a 17th Century Scientist*, 2nd ed. (Berlin: Springer, 2018) (hereafter BOP), p. 651. All translations are from BOP unless the Latin is provided in the footnote, in which case they are mine.

[3] For in-depth studies of the *Elementorum myologiæ specimen* see Troels Kardel, *Steno on Muscles: Introduction, Texts, Translations*, (Philadelphia: The American Philosophical Society, 1994); Raphaële Andrault, "Mathématiser l'anatomie: la myologie de Stensen (1667)," *Early Science and Medicine*, 15 (2010), pp. 505-536; Domenico Bertoloni Meli, "The Collaboration between Anatomists and Mathematicians in the mid-Seventeenth Century with a Study of Images as Experiments and Galileo's Role in Steno's Myology," *Early Science and Medicine*, 13:6 (2008), pp. 665-709.

[4] Nicolaus Steno, *De solido intra solidum naturaliter contento dissertationis prodromus* (Florence, 1669), 78-80; BOP, pp. 822-825. See also Alan Cutler, *The Seashell on the Mountaintop: A Story of Science, Sainthood, and the Humble Genius Who Discovered a New History of the Earth* (New York: Dutton, 2003), pp. 105-118.

[5] Kirsti Andersen and Henk Bos, "Pure Mathematics," in Katharine Park and Lorraine Daston (eds.), *Cambridge History of Science, vol. 3: Early Modern Science*, pp. 696-723, esp. 702.

[6] Peter Dear, *Discipline and Experience: The Mathematical Way in the Scientific Revolution* (Chicago: Chicago Press, 1995), pp. 32-44; Rivka Feldhay, "The use and abuse of mathematical entities: Galileo and the Jesuits revisited," in Peter Machamer (ed.), *The Cambridge Companion to Galileo* (Cambridge: Cambridge Univ. Press, 1998), pp. 80-145, esp. 83-100.

[7] Dear, *Discipline and Experience*, pp. 32-62, 151-79.

[8] Peter Dear, "Mixed Mathematics," in P. Harrison, R. Numbers and M. Shank (eds.), *Wrestling with Nature: From Omens to Science* (Chicago: Chicago Press, 2011), p. 156; Dear, *Discipline and Experience*, 172-9.

[9] August Ziggelaar (ed.), *Chaos: Niels Stensen's Chaos-manuscript with Introduction, Notes and Commentary* (Copenhagen: Danish Library of Science and Medicine, 1997), p. 122; Athanasius Kircher, *Magnes sive de arte magnetica* (Cologne, 1643), pp. 527-9.

[10] This was also the case for the anatomist Fabricius d'Acquapendente (1533-1619), see Peter Distelzweig, "Fabricius's Galeno-Aristotelian

described as a mechanical philosopher, this does not mean that he followed strictly the mechanical philosophies of René Descartes (1596-1650) and Pierre Gassendi (1592-1655).[11] Many non-mechanical, early-modern scholars also used quantification methods and mechanical analogies in medicine and anatomy, as seen in the case of the vitalist Johannes Baptista Van Helmont (1580-1644) and the Aristotelian William Harvey (1578-1657).[12]

Steno's early interests in mathematics have two important historical implications. First, they provide a more complete picture of Steno's personal interest in mathematics. Steno never wrote about what made him turn towards a geometrical explanation of the muscles or when he decided to do it. But historians tend to associate this mathematical turn with the mathematical school of Galileo, whose followers Steno met in Italy in 1666.[13] Giovanni Alfonso Borelli (1608-1679), a mathematician trained in the school of Galileo, also published, more than ten years after Steno, the *De motu animalium* (Rome, 1680-1), a two-volume book on the motion of animals similar to Steno's *Elementorum myologiæ specimen* in many ways.[14] A few months after arriving in Florence, Steno asked Borelli to "teach him some things of geometry," as Borelli reported in a letter to Marcello Malpighi (1628-1694).[15] Moreover, it was in collaboration with the mathematician Vincenzo Viviani (1622-1703), Galileo's last disciple, that Steno published the *Elementorum myologiæ specimen*, as historian Domenico Bertoloni Meli explains.[16] Thus, it would seem reasonable to assume that Steno travelled to Tuscany to learn mathematics in the Italian school of "the great Galileo," as Steno later referred to him.[17]

However, a letter recently acquired by the Royal Danish Library suggests that Steno's interests in mathematics were more developed than previously thought before his arrival in Italy. In the same year of Steno's arrival, Prince Leopoldo de' Medici (1617-75) mentioned to a friend the arrival of "Mr. Steno, a Danish anatomist of young age but remarkable in his work… and a great geometer."[18] This means that Steno displayed his mathematical skills to the Medici Prince before having any prolonged contact with Borelli and Viviani. While this does not diminish the influence of a Galilean school after Steno's arrival in Italy, it implies that Steno's mathematical interests and training predated his Italian years. This is evident, for example, in Steno's *De musculis et glandulis observationum specimen* (Copenhagen, 1664), where Steno had already developed an early geometrical theory of the muscles.[19] But besides the muscles, there has been little historical work done on Steno's early interests in mathematics until now.[20]

The second historical implication of Steno's early interest in mathematics has to do with the development and spread of mixed mathematics into the discipline of anatomy in the second half of the seventeenth century. Steno's interests in mathematics developed gradually with his anatomical works, especially those on the glands. These works are representative of the new anatomical research of the 1660s, based not only on new dissection methods such as the regular prac-

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Teleomechanics of Muscle," in Justin Smith (ed.), *The Life Sciences in Early Modern Philosophy* (Oxford: Oxford Univ. Press, 2014); see also Alan Gabbey, "What Was 'Mechanical' about 'The Mechanical Philosophy'?," in C. Palmerino and J. Thijssen (eds.), *The Reception of the Galilean Science of Motion in Seventeenth-Century Europe* (Dordrecht: Springer, 2004), pp. 11-24, esp. 21-23.

[11] For a recent account of the complexity of early modern mechanical philosophies see D. Bertoloni Meli, *Mechanism: A Visual, Lexical and Conceptual History* (Pittsburgh: University of Pittsburgh Press, 2019), pp. 3-24.

[12] For quantification in Van Helmont, see William Newman and Lawrence Principe, *Alchemy Tried in the Fire: Starkey, Boyle, and the Fate of Helmontian Chymistry* (Chicago, Univ. of Chicago Press, 2002), pp. 56-91; for Harvey as a non-mechanical philosopher despite his use of mechanical analogies see P. Distelzweig, "'Mechanics' and Mechanism in William Harvey's Anatomy: Varieties and Limits," in P. Distelzweig, B. Goldberg and E. Ragland, *Early Modern Medicine and Natural Philosophy* (Dordrecht: Springer, 2016), pp. 117-40.

[13] See Gustav Scherz's biography in BOP, pp. 185-193; Roberto Angeli, *Niels Stensen* (Turin: Edizioni San Paolo, 1996; 1st ed., 1968), pp. 120-127.

[14] See, for example, Richard Westfall, *The Construction of Modern Science: Mechanisms and Mechanics* (Cambridge: Cambridge Univ. Press, 1977), pp. 94-96; and Thomas Settle, "Borelli, Giovanni Alfonso," in *Complete Dictionary of Scientific Biography*, vol. 2. (Detroit, MI: Charles Scribner's Sons, 2008), pp. 306-314. For Borelli's mathematical training see Bertoloni Meli, "The Collaboration between Anatomists and Mathematicians," p. 678. Most of Borelli's books up to then were all on mathematics.

[15] Borelli to Malpighi, 17 July 1666, in Howard Adelmann, *The Correspondence of Marcello Malpighi*, 5 vols. (London: Cornell University Press, 1975), vol. 1, p. 318: "lo Stenone è qui, … e mi ha detto … che vuol che io gl'insegni qualche cosa di geometria."

[16] Bertoloni Meli, "The Collaboration between Anatomists and Mathematicians," pp. 696-706.

[17] Steno, *De solido* (Florence, 1669), p. 50; BOP, p. 802.

[18] Leopoldo de' Medici to Alessandro Segni, 27 November 1666, in Copenhagen, Royal Danish Library, Acc. 2019/54: "il S. Stenone Danese Anatomico gioviane d'età ma insigne nel suo mestiere corredato poi d'ogni sorte di laudazione, e geometra bravo il che molto li giova al suo mestiere et il vero tipo della modestia." Although some dated the letter April 1666, Leopoldo's handwriting says "Nov. 1666."

[19] Troels Kardel, *Steno: Life, Science, Philosophy* (Copenhagen: The Danish National Library of Science and Medicine, 1994), pp. 25-32; Kardel, *Steno on Muscles*, pp. 11-16; Bertoloni Meli, "The Collaboration between Anatomists and Mathematicians," pp. 697-699.

[20] The few works that mentioned Steno's research on the glands barely addressed any mathematics, see Harald Moe, "When Steno Brought New Esteem to Glands," in J. Poulsen and E. Snorrason (eds.), *Nicolaus Steno 1638-16868: A Re-consideration by Danish Scientists* (Gentofte, Denmark: Nordisk Insulinlaboratorium, 1986), pp. 51-96. For a brief mention of the mechanical aspect of Steno's study on glands see D. Bertoloni Meli, *Mechanism, Experiment and Disease: Marcello Malpighi and Seventeenth-Century Anatomy* (Baltimore: Johns Hopkins University Press, 2011), pp. 16, 103-6.

tice of dissections and vivisections, but also on new areas of anatomical interest such as the glands, the lymphatic system, and the circulation of the blood.[21] It was in this anatomical context that Steno used quantitative measurements, mechanical analogies, and the concepts of flow and speed in his anatomical argumentation. Some of these methods had already been used by other anatomists such as William Harvey, Santorio Santorio (1561-1636) and even Galen.[22] For instance, Galen used the quantities of fluid drank (and later expelled) by a man to argue that urine was drawn directly from the blood.[23] Yet, the epistemological role of mathematics was rapidly changing in the seventeenth century and, more importantly, it was still a matter of debate in natural philosophy and medicine. Therefore, a look at Steno's early uses of mathematics helps to see exactly how an early modern anatomist adopted such methods. This article's structure follows the chronological line of Steno's anatomical publications before the *Elementorum myologiæ specimen*, from 1661 to 1664. For reasons of space, I focus mostly on the intellectual aspects of Steno's interest in mathematics, setting aside other considerations.

WEIGHTS AND PROPORTIONS OF GLANDS, 1661

Nicolaus Steno arrived in the Netherlands for the first time sometime before April 1660.[24] He had already studied for three years at the University of Copenhagen under Thomas Bartholin (1616-1680), one of the leading physicians of Europe and a strong promoter of a new anatomy based in regular dissections.[25] In those years, Steno became familiarized with the most recent anatomical findings, including the discovery of the circulation of the blood by William Harvey and the lymphatic vessels by Bartholin himself.[26] In his third year, university classes were canceled due to a Swedish military siege imposed on Copenhagen, and so Steno used his time to read beyond the normal university curriculum, engaging with recent scientific literature associated with the new sciences, including some books related to mathematics.[27] According to the notebook that he wrote in that year, Steno read in full Jean Pecquet's (1622-1674) *Experimenta nova anatomica* (Paris, 1654), a book which Pecquet wrote in collaboration with the French mathematicians Gilles Personne de Roberval (1602-1675) and Adrien Auzout (1622-1691), and he also read the original and long description of Pierre Gassendi's (1595-1655) mechanical and atomistic philosophy.[28] When Steno left Denmark, although his intellectual commitment was to anatomy, he was aware of the new scientific trends flourishing throughout Europe.

Steno's years in the Low Countries confirm his commitment to anatomy. In those years, while still in his early twenties, Steno earned a solid reputation for his dissection skills among those who witnessed his dissections either in person or through his writings.[29] Steno lived in Amsterdam from March to July 1660, where he took classes of anatomy with Gerard Blasius (1625-1682) and where he also observed for the first time the parotid salivary duct, later named as *ductus stenonianus*.[30] Steno then moved to the University of Leiden, where his mentor Thomas Bartholin had also been twenty years before.[31] There, Steno met the physicians Franciscus Sylvius (1614-1672) and Johannes Van Horne (1621-1670), old friends of Bartholin who were now prestigious pro-

[21] Frequent dissections and vivissections only became common in the second half of the 17th century, see Anita Guerrini, *The Courtiers' Anatomists: Animals and Humans in Louis XIV's Paris* (Chicago: University of Chicago Press, 2015), pp. 6, 24; D. Bertoloni Meli, "Early Modern Experimentation in Live Animals" in *Journal of the History of Biology*, 46 (2013), pp. 199-226. These areas of interest expanded upon the two major discoveries of the late 1620s: the circulation of the blood by William Harvey and the lacteal vessels (the lymphatics) by Gaspare Aselli (1581-1625), whose works were often published together, see Domenico Bertoloni Meli, *Mechanism, Experiment and Disease: Marcello Malpighi and Seventeenth-Century Anatomy* (Baltimore: Johns Hopkins University Press, 2011), pp. 1-4, 31-7.

[22] For quantification and the use of concepts of flow by both Galen and Harvey see Michael Shank, "From Galen's Ureters to Harvey's Veins," *Journal of the History of Biology*, 18 (1985), pp. 331-55. For Galen's mechanical analogies see Bertoloni Meli, *Mechanism*, pp. 11-16. On Santorio and Harvey see Fabrizio Bigotti, "The Weight of the Air: Santorio's Thermometers and the Early History of Medical Quantification Reconsidered," *Journal of Early Modern Studies* 7 (2018), pp. 73-103; and Jerome Bylebyl, "Nutrition, Quantification and Circulation," *Bulletin of the History of Medicine*, 51 (1977), pp. 369-385.

[23] Owsei Temkin, "A Galenic model for quantitative physiological reasoning?" *Bulletin of the History of Medicine*. 35 (1961), pp. 470-475, esp. 471-472.

[24] Scherz's biography in BOP, p. 68.

[25] For more on Bartholi in English, see C. D. O'Malley, "Bartholin, Thomas," *Complete Dictionary of Scientific Biography*, vol. 1, pp. 482-3.

[26] Scherz's biography in BOP, pp. 47-50.

[27] For an overview of what Steno read, see Ziggelaar, "Commentary," in Ziggelaar (ed.), *Chaos*, pp. 459-481.

[28] Ziggelaar, "Commentary," pp. 473-474. On Pecquet and mathematicians see Bertoloni Meli, "The Collaboration between Anatomists and Mathematicians," pp. 670-7.

[29] Scherz's biography in BOP, pp. 72-83, 151, 367; Guerrini, *The Courtiers' Anatomists*, pp. 85-87.

[30] First named as such by Johannes Van Horne in Van Horne, *Mikrokosmos seu brevis manuductio ad historiam corporis humani* (Leiden, 1662), p. 23. See also Henry Gray, *Anatomy of the Human Body*, 20th ed. (Philadelphia, Lea & Febiger, 1918), p. 1134.

[31] Steno enrolled in the University of Leiden in 27 July 1660, see Leiden University Library, ASF 10, fol. 585; as quoted in *Album studiosorum Academiæ Ludguno Batavæ* (The Hague, 1875), p. 482. For Bartholin in Leiden see O'Malley, "Bartholin, Thomas," p. 482.

fessors of medicine and anatomy at the University.[32] Under their guidance, Steno continued his explorations of the salivary duct and salivary glands. Upon the suggestion of Sylvius and Bartholin, Steno published his first anatomy book, the *Anatomica disputatio de glandulis oris* (Leiden, 1661), the outcome of a university dissertation defense at Leiden, presided by Van Horne.[33] The book was published with the Elsevier printers, the same house that published Galileo's *Two New Sciences* (Leiden, 1638) a few decades earlier. In this short book, Steno put forward a full description of the salivary glands, the most complete up to then, in a time in which studies on the glands were emerging as a new area of anatomical research.[34] Half a year later, Steno re-edited his text as the first part of a four-part book in 1662, the *Observationes anatomicae* (Leiden, 1662). This new book, which was distributed more widely, included Steno's research not just on the salivary, but also on the lachrymal and nasal glands. Although a single book, the four parts of the *Observationes anatomicae* show Steno's intellectual progress and how he gradually used more methods and ideas from the physico-mathematics, which he increasingly acknowledged.

This research program on the glands started when Steno observed for the first time the parotid salivary duct, first in a sheep's head and then in a dog.[35] This duct proceeded directly from the parotid gland, located behind the ear, to the mouth. But the most recent book on glands, the *Adenographia sive glandularum totius corporis descriptio* (London, 1656), written by the English physician Thomas Wharton (1614-1673), had no mention of this duct.[36] The *Adenographia* was the first anatomical publication entirely dedicated to glands, so studies of glands still had much to develop, as the works of Steno and Sylvius show.[37] Wharton described the parotid

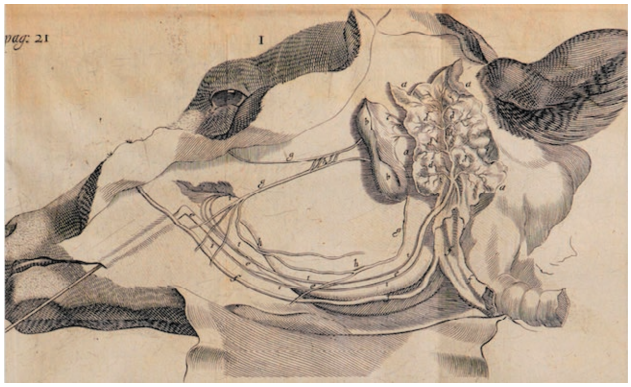

Figure 2. Parotid glands in the head of a calf. a) the largest is the conglomerate gland with c) the salivary duct, and b) the bean-shaped conglobate gland. From Steno, *Observationes anatomicae* (Leiden, 1662), p. 21. Courtesy of Wellcome Collection.

gland in detail, but he did not relate it to the production of saliva because, as Steno explained, he saw no salivary duct.[38] For Wharton, saliva was produced only in the maxillary glands, where he observed a pathway between them and the mouth, now called *ductus whartonianus*.[39]

But there were other things that Wharton missed. According to Steno, the parotid gland described by Wharton was actually formed by two distinct glands, the *conglobate* parotid gland, connected to the lymphatic system, and the *conglomerate* parotid gland, connected to the mouth via the salivary duct (fig. 2).[40] Here, Steno was following the twofold division between conglobate and conglomerate glands, developed by his professor Franciscus Sylvius.[41] The conglobate glands were round organs directly connected to the lymphatic vessels, and the conglomerate were larger organs that released fluids into the body, such as salivary or the pancreatic fluids. Although Sylvius explained this distinction in his writings, Steno said he learned it directly from his professor's dissections at the hospital in Leiden, where "medical practice" was taught "daily."[42]

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[32] Bartholin participated in Sylvius' dissections around the year 1640, see Johannes Walaeus letter to Thomas Bartholin, 10 October 1640 in T. Bartholin, *Institutiones anatomicae* (1641), p. 408. Van Horne wrote the letter "De aneurysmate epistola" published in Thomas Bartholin, *Anatomica aneurysmatis dissecti historia* (Palermo, 1644).

[33] Nicolaus Steno, *Observationes anatomicae quibus varia oris, oculorum, et narium vasa describuntur* (Leiden, 1662), p. 5 (BOP, p. 430).

[34] Bertoloni Meli, *Mechanism, Experiment and Disease*, pp. 103-106.

[35] Steno to Bartholin, 22 April 1661, in Bartholin, *Epistolarum Medicinalium Centuria III* (Copenhagen, 1667), pp. 88-89: "quod 7 April mihi emptum in Museolo solus secabam ovillo capite ductum, à nemine, quod sciam, descriptum invenirem. … et paucis inde diebus in canino capite licet obscurius successit." (BOP, pp. 420-421). For this research of the parotid duct Steno also dissected a lamb, a cow, many more dogs, rabbits and he mentioned Sylvius' dissections of human cadavers at the hospital, see Steno, *Observationes anatomicae*, §16, §18, §47-48, §50, §19, pp. 15, 17, 46-47, 49, 18-19 (BOP, pp. 436, 438, 457-458, 460, 439).

[36] For an English translation see Stephen Freer (transl.), *Thomas Wharton's Adenographia* (Oxford: Oxford University Press, 1996).

[37] Andrew Cunningham, "The historical context of Wharton's work on the glands," in *Thomas Wharton's Adenographia* (Oxford, 1996), pp. xxvii-xxxi.

[38] Steno, *Observationes anatomicae*, p. 15: "sed non mirum haec à Clarissimo viro proposita, quandoquidem praeter vasa cæteris partibus communis nihil in illa observavit." (BOP, p. 437); Thomas Wharton, *Adenographia* (London, 1656), pp. 124-7.

[39] See Steno, *De musculis et glandulis* (Copenhagen, 1664), p. 40; Gray, *Anatomy of the Human Body*, p. 1135.

[40] Steno, *Observationes*, §10, p. 10: "Ut itaque distinctè considerentur, poterit hæc de qua nobis sermo est, parotis conglomerata appellari, nomine conglobatarum parotidum reliquis relicto." (BOP, p. 433).

[41] Steno, *Observationes anatomicæ*, §9, p. 7 (BOP, p. 432); Bertoloni Meli, *Mechanism, Experiment and Disease*, p. 103.

[42] Steno, *Observationes anatomicæ,* §10, p. 9: "Superiori enim anno iam præcipite, cùm in Nosocomio praxin faciendo quotidie doceret Clariss.

To show better Wharton's mistake, instead of arguing on the basis of dissections alone, Steno put forward another argument using quantitative measurements. For some glands, including the maxillary and the parotid glands, Wharton registered their weights in different animals (table 1). The proportions between the weights of the two glands measured by Wharton in a man and in a fetus of a cow were somewhat similar, averaging approximately 0.6. This proportion showed that the parotid had almost twice the weight of the maxillary glands. However, Steno argued that the parotid glands were not as heavy as Wharton thought, mainly because they were two separate glands, the conglobate and the conglomerate. Steno said that in Wharton's case the proportion between the parotid and maxillary glands

> has not been exactly observed … [unless] besides bigger and more numerous nerves reported through the upper gland, the smaller [conglobate] gland enclosed in the larger [conglomerate gland] increased the weight of the latter, insofar as it was [thought to be] not distinct from the other.[43]

Table 1. Data from Wharton, *Adenographia*, pp. 119-120, 125 and Steno, *Observationes*, pp. 10-11. The conversion of units from 17th-century ounces to grams is from Wilhelm Maar (ed.), *Nicolai Stenonis Opera Philosophica*, 2 vols. (Copenhagen: Vilhelm Tryde, 1910), vol. 1, pp. 227-228.

Dissected corpses	Maxillary Gland	Parotid Gland	Proportion
28-year-old man (Wharton)	9.8 g	17.6 g	0.56
fetus of a cow (Wharton)	7.8 g	11.7 g	0.67
	proportion average for Wharton's values		**0.62**
calf (Steno)	125 g	141 g	**0.89**

To show better his point, Steno measured the weights of the glands in a calf he dissected. This time, however, the parotid gland was "free from vessels and from the conglobate gland lying beside it."[44] In the end, Steno's proportion of the weights of the maxillary and the parotid conglomerate glands was 0.89, much closer to 1, thus meaning that their weights did not differ much. Neither Steno nor Wharton wrote the precise proportion in a structured format like table 1, but they both referred to it.[45] More importantly, with this measurement Steno used a quantitative argument to confirm his point on the separation of the conglobate and conglomerate parotid glands, which Wharton missed. Since by definition conglomerate glands secreted a fluid and Steno had found a salivary duct coming out of it, this quantitative point also had an implication on the function of the glands and thus contributed to Steno's argument that the parotid conglomerate gland produced salivary fluid.

For a modern scientist, it could be tempting to judge Steno and Wharton for drawing conclusions on these proportions without enough comparative data, i.e. for lacking what modern science now understands as observational error.[46] However, in the middle of the seventeenth century, when the epistemological value of experiments was still being debated, there was nothing akin to a statistical theory of error.[47] In fact, notions of how to perform experiments, and how to report them, were even evolving between Steno and Wharton themselves. Both authors decided to measure and compare the weights of the glands, but there were significant differences in their approaches. First, Steno pointed out that Wharton's quantitative data was not precise enough, since Wharton did not say what exactly he had weighed: was it the glands and the attached vessels, or did he remove blood vessels and nerves from the glands beforehand? In Steno's words, Wharton "seems to have described an abundance of matter from these glands in an undetermined quantity [*extensione non determinata*]."[48] This remark also conveys Steno's understanding of a need to describe the experimental conditions better. Steno tried to improve upon Wharton, by saying he detached each gland that he

Franciscus Sylvius exhibuit tum discipulis…" (BOP, p. 433).

43 Steno, *Observationes,* §12, p. 11: "Ne tamen huius ad illam proportionem exacte observatam esse credam, suadet, præter nervos majores copiosioresque per superiorem delatos, minor majori inclusa glandula, quam, utpote a reliqua non distinctam, pondus illius auxisse puto." (BOP, p. 434).

44 Steno, *Observationes,* §12, p. 11: "à vasis et sibi apposita conglobata liberatam" (BOP, p. 434).

45 Steno, *Observationes,* §12, p. 11: "proportione exactè observatam."

46 Stephen Stigler, *The History of Statistics: The Measurement of Uncertainty before 1900* (Cambridge, MA: Harvard Univ. Press, 1986), esp. 90-1; Lorraine Daston, *Classical Probability in the Enlightenment* (Princeton, NJ: Princeton University Press, 1988), esp. 271-2; Ian Hacking, *The Emergence of Probability: A Philosophical Study of Early Ideas About Probability Induction and Statistical Inference*, 2nd ed. (Cambridge: Cambridge University Press, 1975, 2006), p. 130.

47 For seventeenth-century debates on experiments see Steve Shapin and Simon Schaffer, *Leviathan and the Air Pump: Hobbes, Boyle, and the Experimental Life* (Princeton: Princeton University Press, 1985), esp. 225-282; Dear, *Discipline and Experience,* pp. 63-85. For the historical value of approaches that would today be considered wrong see Jed Buchwald and Allan Franklin (eds.), *Wrong for the Right Reasons* (Dordrecht: Springer, 2005).

48 Steno, *Observationes anatomicæ*, §12, pp. 10-11: "Quibus Clariss[imus] Vir copiam materiæ expressisse videretur, extensione non determinata, nisi jam ante constare putasset, materiam in utraque eodem modo esse dispositam, quod & innuit, dum substantiam utrique similem adscribit." (BOP, p. 434).

weighed "from vessels and from the conglobate gland lying beside it."[49] Finally, whereas Wharton presented the weights only as a secondary detail of his anatomical description, Steno used them to argue for the existence of two glands – the conglobate and conglomerate glands. Ultimately, in Steno's text, the careful description of how he carried out the measurements and the details he included lent them a greater epistemological value than they had for Wharton.

Steno did not use more quantitative measurements in the *Observationes*, but he resorted to other mathematical approaches.[50] After establishing the distinction between the conglobate and conglomerate parotid glands, Steno explained that the function of the latter was to produce the salivary fluid, alongside the maxillary glands, already discovered by Wharton.[51] In fact, Steno discovered other glands that produced saliva and he listed five types in total: parotid glands, maxillary glands, sublingual glands, palatine glands and glands of the cheek.[52] Although Steno did not comment on the fluid production rates each gland, he said that "several small vessels in the mouth" transmitted "fluid equally to all parts [*ad humorem omnibus æqaliter communicandum*]."[53] He concluded that the fluid reached all parts equally "in order that the upper parts moisten as well as the lower ones, [and] the internal as well as the external ones."[54] Later, when discussing the constitution of the saliva, which Steno said required "chymical anatomy," he used the same kind of discourse, in which he spoke of a quantifiable entity without actually measuring it.[55] First, he said that "tasting and smelling" saliva was similar to water because it was "deprived of quality," however "seeing and feeling [it] judge it less simple than water."[56] Again, Steno was following the methods of his professor Franciscus Sylvius who relied strongly on the senses as a source of information about the constitution of chymical substances.[57] Indeed, Steno concluded that saliva was not "a simple liquid, but a mixed one, and this in a proportion [*singulari proportione*]."[58] But this proportion was discussed only in qualitative terms, even by "the famous Sylvius … [who] thinks that in saliva there is much water, a little volatile spirit and very little lixivial salt mixed with, and moderated by a trace of oil and spirit of acid."[59]

THE MECHANICAL ACTION OF BODILY FLUIDS, 1661-1662

Steno finished the 1661 version of his treatise on the salivary glands with a set of corollaries on the role of the mind on blood circulation, on the glands of the nose and on the filtering of blood in the body, which he expanded in the other treatises of the *Obsevationes anatomicae*.[60] Corollaries were a structure most common in mathematical treatises, usually associated with Euclid's *Elements*, but also typical of academic dissertations.[61] Steno did not use a corollary structure in the *Observationes*, as he would later do in his final book on the muscles. But in its third treatise, on the lachrymal glands, Steno became much more open when speaking about mechanics and using mathematical concepts. First, he dedicated the third treatise to six intellectuals from the Low Countries and Denmark, two of them mathematicians.[62] One was Jorgen Eilersen (Georgius Hilarius) (1616-1686), a Danish theologian who graduated from the University of Copenhagen and the headmaster of the Latin School of Copenhagen, which Ste-

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[49] Steno, *Observationes,* §12, p. 11: "à vasis et sibi apposita conglobata liberatam" (BOP, p. 434).

[50] Wharton, on the other hand, did include more measurements, as when he said that the maxillary duct in a cow was thirteen inches long, see Wharton, *Adenographia*, p. 131: "ductu tredecim pollices longo provehitur"

[51] Steno, *Observationes*, §17, p. 17: "Verus Parotidum conglomeratarum usus, illam, quæ per ductum salivarem exteriorem in exteriorem oris cavitatem excernitur, salivam præparare…" (BOP, p. 438)

[52] See Steno, *Observationes anatomicæ*, §9, p. 8 (BOP, p. 432). For a description of the cheek, sublingual and palatine glands, see idem, §18, §20, §21, pp. 17-23 (BOP, pp. 438-440).

[53] Steno, *Observationes anatomicæ*, §22, p. 22: "plura data sunt vascula ad humorem omnibus æqualiter communicandum" (BOP, p. 440).

[54] Steno, *Observationes*, §22, p. 22: "Ut autem in ore cum inferioribus superiora, interiora cum exterioribus madefierent" (BOP, p. 440)

[55] Steno, *Observationes*, §25, p. 24: "consideratio Chymicam Anatomen requirat" (BOP, p. 441).

[56] Steno, *Observationes*, §28, p. 26: "Quam itaque sapor, et odor ἄποιον iudicant, eam visus, et tactus aqua minus simplicem decernunt" (BOP, p. 444).

[57] Evan Ragland, "Chymistry and Taste in the Seventeenth Century: Franciscus Dele Boë Sylvius as a Chymical Physician Between Galenism and Cartesianism," *Ambix* 59 (2012), pp. 1-21. On the use of the word "chymistry" see Lawrence Principe, *The Secrets of Alchemy* (Chicago: University of Chicago Press, 2013), p. 85.

[58] Steno, *Observationes anatomicæ*, §28, p. 27: "Esse iitaque non simplicem liquorem, sed mixtum, idque singulari proportione, ex ante dictis patet." (BOP, p. 445).

[59] Steno, *Observationes anatomicæ*, pp. 27-28: "Clarissimi Sylvius … existimat esse in saliva multum aquæ, parum spiritus volatilis, et minimum salis lixiviosi, cum olei spiritusque acidi tantillo misti, temperatique." (BOP, p. 445). F. Sylvius, *Opera medica, hoc est, disputationum medicarum decas* (Geneva, 1681), p. 11.

[60] Steno, *Disputatio de glandulis oris* (Leiden, 1661) (BOP, pp. 462-463).

[61] For the use of corollaries in Dutch seventeenth-century dissertations, see Dirk Van Miert, *Humanism in an Age of Science: The Amsterdam Athenæum in the Golden Age, 1632-1704* (Leiden: Brill, 2009), p. 153-6. For an extensive study of dissertations in the early modern period, see Kevin Chang, "From Oral Disputation to Written Text: The Transformation of the Dissertation in Early Modern Europe," *History of Universities* 19 (2004), pp. 129-187.

[62] Steno, *Observationes anatomicæ*, pp. 80-81 (BOP, p. 483).

no attended before the university.[63] Although Eilersen was academically trained in theology, he wrote several books on mathematics in Copenhagen, where he also edited astronomical calendars and almanacs.[64] In fact, Steno addressed him as a "mathematician and man of letters."[65] Eilersen was later appointed as Professor of Mathematics at the University of Copenhagen.[66] The other mathematician was Jacob Golius (1596-1667), professor of mathematics at the University of Leiden since 1629.[67] Steno was friends with Golius, since they discussed topics besides anatomy or mathematics, as when Golius informed Steno about the emergence of fevers in Amsterdam in September 1661.[68] Golius also "did not disdain either to watch when I [Steno] prepared the salivary and lacrimal ducts in a calf," showing that he sometimes attended Steno's dissections.[69]

In this third treatise of the *Observationes,* Steno explained the production of tears in the eye glands and how they move from the glands to the eyes. But before starting his main narrative description of the lachrymal glands, Steno wrote an introduction where he points out the importance of lubrication in mechanical motion. He explains that those who work on mechanics know that, "to facilitate movement, the things to be moved should be smeared by some oily humor."[70] He compares the oil to a third agent that facilitates the mover, like pushing a boat over a surface with the help of rollers laid underneath (fig. 3) or "smearing with an unctuous fluid the axle about which the wheel rotates."[71] Like these mechanisms, Steno continues, the bodies of animals also rely on fluids to make the parts move better. But, unlike machines, the living body "proceeds more skillfully or, I should say, more divinely," because "both the fluid that is supplied and the quantity in which it is supplied show a skill far greater."[72] According to him, this was seen in the mouth with salivary fluid's enhancement of the movements of the mouth, but most especially in the eyes.[73]

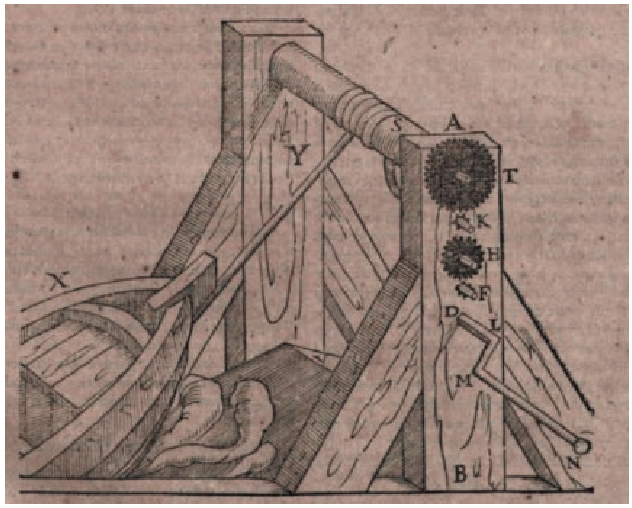

Figure 3. Pulling a boat over a flat surface with the help of rollers laid underneath from Simon Stevin, *Les Œuvres Mathématiques* (Leiden, 1634), p. 481. Courtesy of Special Collections, The Sheridan Libraries, Johns Hopkins University.

The analogy between artificial mechanisms and the human body in the works of Steno and other scholars is often attributed to the widespread influence of Cartesian thought, especially in the Netherlands.[74] How-

[63] Gustav Scherz's biography in BOP, pp. 29-31. On Eilersen see S. M. Gjellerup, "Eilersen, Jorgen" in Carl Frederik Bricka (ed.), *Dansk biografisk Lexikon* (Copenhagen, 1887-1905), vol. 4, pp. 464-465; and Maar, *Nicolai Stenonis Opera Philosophica*, vol. 1, p. 241.

[64] J. Eilersen, *Trigonometria plana* (Copenhagen, 1644); Eilersen, *Progymnasmatum mathematicorum enchiridion* (Copenhagen, 1656).

[65] Steno, *Observationes anatomicæ*, p. 80: "D. Georgio Hilario, Mathematico et Literatori" (BOP, p. 483).

[66] For Eilersen's university appointment see Gjellerup, "Eilersen, Jorgen."

[67] W. Juynboll, "Golius, Jacob," in P. C. Molhuysen and P. J. Blok (eds.), *Nieuw Nederlandsch Biografisch Woordenboek*, 10 vols. (Leiden, 1911-1937), vol. 10 (1937), pp. 287-289; and "Golius, Jacobus" in A. J. van der Aa (ed.), *Biographisch woordenboek der Nederlanden*, 21 vols. (Haarlem, 1852-1878), vol. 7, pp. 270-3.

[68] Steno to Thomas Bartholin, 12 September 1661, in Thomas Bartholin, *Epistolarum Medicinalium Centuria III* (Copenhagen, 1667), p. 230: "et retulit mihi ante paucos dies Clariss. Golius sibi à Medicó quos dam Amstelodamensi per litteras relatuum…" (BOP, p. 468).

[69] Steno, *Observationes anatomicæ*, p. 59: "Sed nec Clariss. Golius Mathematum et Orient. Ling. Profess. Præceptor colendus cum salivæ et lachrimarum vasa in bubulo adornarem, spectatorem agere dedignatus est." (BOP, pp. 470-1).

[70] Steno, *Observationes anatomicae*, p. 85: "ut ad motum faciliorem reddendum res movendas humore unctuoso oblinerent" (BOP, p. 484).

[71] Steno, *Observationes anatomicae*, p. 85: "Viderunt illi, si movendum inter et fixum, super quod motus fieri debet, tertium motu facilius intercedat, opus longe commodius procedere, hinc, ut suppositis cylindris in æquora navem propellunt, sic et, super quem rota volvitur, polum liquore pinguiori inungentes gyrationem facilius expediunt." (BOP, p. 485).

[72] Steno, *Observationes anatomicae*, p. 86: "In automatico autem animalium corpore artificiosius, imo divinius hæc omnia geruntur; ibi enim et humor, qui subministratur, et, quo subministratur, modus longe maius artificium commonstrant."

[73] Steno, *Observationes anatomicae*, p. 86: "Sic partium in ore motus accedente saliva promoventur… Sed præ cæteris in oculis elegantissimè hæc conspiciuntur." (BOP, p. 486).

[74] Eric Jorink says that the Netherlands was "the hotbed" of Cartesian philosophy, in "*Modus politicus vivendi*: Nicolaus Steno and the Dutch (Swammerdam, Spinoza and Other Friends), 1660–1664," in Raphael Andrault and Mogens Lærke, *Steno and the Philosophers* (Leiden: Brill, 2018) pp. 12-44, esp. 16; see also Wiep van Bunge, "The Early Dutch Reception of Cartesianism" in Steven Nadler, Tad M. Schmaltz, Delphine Antoine-Mahut, *The Oxford Handbook of Descartes and Cartesianism* (Oxford: Oxford University Press, 2019); G. A. Lindeboom, "The Impact of Descartes on Seventeenth Century Medical thought in the Netherlands," *Janus*, 58 (1971), pp. 201-206. For the supposed influenced of Cartesianism on Steno, see Sebastian Olden-Jørgensen, "Nicholas Steno and René Descartes: A Cartesian perspective on Steno's sci-

ever, there was already a tradition of using mechanical analogies in anatomy since Galen and Erasistratus.[75] Thomas Wharton, no Cartesian himself, also relied on mechanical analogies, as when he compared a muscle in the mouth to a pulley.[76] There were, however, conceptual differences in the way anatomists adopted these analogies. For instance, like Steno, Galen also commented on the body as superior to machines, but he did it mostly to show that mechanical analogies fell short of the full anatomical reality.[77] Steno explained that the body differed from a machine not in the mechanism itself but in "the humour which is supplied," which reveals "a skill far greater."[78]

But there is more to be said about these mechanical analogies beyond the typical Cartesian comparison of bodies to machines. Mechanics was considered part of physico-mathematics. Thus, in Steno's mind, those who studied and practiced mechanics, the "*mechanici*" as he called them, relied on mathematics as their main tool to describe the natural world.[79] Steno in particular had in mind the work of "the most talented [Simon] Stevin," one of the leading names of Dutch mathematics, and whom Steno mentioned in the preface.[80] In the seventeenth century, one of the main arguments for the study of mechanics was the command it gave its practitioners over phenomena whose operations were marvelous and unseen, like the use of a lever to lift weights that were impossible to lift otherwise. This description fits well with Steno's understanding of the human body, which he described as even more marvelous than inert mechanisms, as we saw. By adopting mechanical analogies, like Descartes and others had done, Steno was looking for an approach to make the invisible operations of the human body visible. Jesuit scholars such as Athanasius Kircher and Gaspar Schott (1608-1666), whom Steno read in his final year in Copenhagen, also used physico-mathematics to unmask the hidden phenomena of nature.[81] Steno returned to this idea of using mathematics to illustrate hidden phenomena in his preface to the *Elementorum myologiæ specimen*, where he insisted that, by neglecting mathematics, "anatomy has brought the matter to such a point that nothing remains more unknown to man than man himself."[82]

SPEED AND FLOW OF BLOOD, TEARS, AND SALIVA, 1662

Steno gestured towards mathematical concepts one more time in his explanation of how the eye glands produced lachrymal fluid. As typical in an anatomical treatise, Steno begins by describing the structure of the glands, agreeing with Wharton's description of the two conglomerate glands of the eye, which they both called the lachrymal and innominate glands.[83] But when addressing the function of the glands, Steno explains, Wharton and others "did not believe that such an abundance of tears can possibly come forth from such small glands."[84] In fact, the large quantity of tears that often come to the eye led Wharton to agree with Hippocrates

entific development," Gary Rosenberg (ed.), *The Revolution in Geology from the Renaissance to the Enlightenment* (The Geological Society of America, 2009), pp. 149-57; and Stefano Miniati, *Nicholas Steno's Challenge for Truth* (Milan: Franco Angeli, 2009), p. 95.

[75] Evan Ragland, "Mechanism, the Senses, and Reason: Franciscus Sylvius and Leiden Debates Over Anatomical Knowledge After Harvey and Descartes," in Peter Distelzweig, Benjamin Goldberg and Evan Ragland (eds.), *Early Modern Medicine and Natural Philosophy* (New York: Springer, 2016), pp. 173-206, esp. 183-4.

[76] Wharton, *Adenographia*, p. 131: "fertur sub musculo maxillari tereti biventri, …, qui eidem ramo quasi *trochlea* vicem præstat." On Wharton as non-Cartesian see Cunningham, "The historical context of Wharton's work on the glands," p. xli; Wharton, *Adenographia*, p. 154: "Hanc opinionem primus proposuit Cartesius, Lib. de affect. art. 31,32 eamque variis rationibus Bartholinus expugnavit, nempe: …"; and Wharton letter to Mrs. Church, 15 May 1673, in Wharton, *Thomas Wharton's Adenographia*, p. 311.

[77] Sylvia Berryman, "Galen and the Mechanical Philosophy," *Apeiron* 35 (2011), pp. 235-53, esp. 242-7.

[78] Steno, *Observationes*, p. 86: "In automatico autem animalium corpore artificiosiùs, imò divinius hæc omnia geruntur; ibi enim et humor, qui subministratur, et, quo subministratur, modus longè maius artificium commonstrant." (BOP, p. 486). Interestingly, even Descartes nuanced his body-machine comparisons, see Gideon Manning, "Descartes' Healthy Machines and the Human Exception," in Daniel Garber and Sophie Roux (eds.), *The Mechanization of Natural Philosophy* (Dordrecht: Springer, 2013), pp. 237-62.

[79] Steno, *Observationes*, p. 85: "Quod Mechanicos usus docuit…"

[80] Steno, *Observationes*, p. 82: "Existimat ingeniosissiimus Stevinus" (BOP, p. 484). For more on Stevin see E. J. Dijksterhuis, "The Life and Works of Simon Stevin," in E. J. Dijksterhuis (ed.), *The Principal Works of Simon Stevin, Vol. 1: General Introduction, Mechanics* (Amsterdam, 1955), pp. 3-14; Dirk Struik, *The Land of Stevin and Huygens: A Sketch of Science and Technology in the Dutch republic during the Golden Century* (London: D. Reidel Publishing Company, 1981), esp. 52-60.

[81] Steno has many notes related to Kircher, but for reference to Kircher and Schott in the same place see Ziggelaar, *Chaos*, pp. 253-4. For Kircher and Schott's approach to hidden phenomena, see Mark Waddell, *Jesuit Science and the End of Nature's Secrets* (Burlington, VT: Ashgate Publishing Company, 2015), esp. 5-15, 161-186.

[82] Steno, *Elementorum myologiæ specimen*, p. iv: "Namque dum legitimi principis [mathematicarum] imperium non agnoscens, suo, … eò rem [anatome] tandem deduxit, ut homine nihi homini manserit ignotius." (BOP, p. 651).

[83] Steno, *Observationes anatomicae*, pp. 86-87: "Glandulæ autem interiorem palpebrarum superficiem humectantes binæ sunt: lacrymis altera Clariss. Whartono innominata dicta …"

[84] Steno, *Observationes anatomicæ*, p. 92: "non enim [magni viri] crediderunt, posse ex tam parvis glandulis tantum lacrymarum copiam prodire" (BOP, p. 490). Wharton, *Adenographia*, p. 178: "Enim verò hæ glandulæ perexiguæ sunt, et multum humiditatis in se coacervare nequeunt, nè vicesima quidem lachrymarum partem quæ tantillo temporis spacio a nonnullis profunduntur."

that tears were produced in the brain.[85] Not only was the brain the largest organ closer to the eye, but, in humans, tears were also related to emotions and pain, felt mainly by the brain and the nervous system.[86] Steno, however, describes both eye glands as conglomerate glands, and so, according to his theory of glands, they produce a fluid, which serves to lubricate the eye or, when produced "profusely… it comes under the name of tears."[87] To address the problem of quantity, Steno uses a simple mathematical explanation, by saying that

> if the magnitude of the [tear]drops is compared to the time during which they are formed, no problem will appear here. For the time is not so short that as much humor could not flow in through several vessels as is required to form a drop.[88]

Steno uses the concepts of time and flow to say that the formation speed of tears is slow enough to produce each tear drop. Later in the same treatise, Steno uses these concepts to put forward a mechanical theory of glandular secretion by blood filtration.

Steno had already suggested that the salivary glands produced saliva directly from the blood, and not, as Wharton claimed, from the nerves.[89] In the first treatise, Steno said that "arteries supply to the glands, besides heat, also nutriment and together with it the matter of saliva."[90] Wharton thought that was unlikely, because there were not sufficient arteries and veins passing through the maxillary glands for "the quantity of salivary matter that is excreted."[91] In order to solve this problem, Steno said that "since saliva does not flow into the mouth with the same speed [*celeritate*] at which blood arrives, the delay of the saliva in its flowing could compensate the paucity of blood arriving more quickly."[92] He explored this idea further in his study of the eye glands. According to him, the glands of the eye do not have to be as large because "all the humor which emanates from the eyes was [not] collected previously in the glands."[93] For Steno, the secretion of lachrymal humor is in fact directly associated with each pulsating passage of arterial blood. As blood flowed normally through the eyes, the glands produce the quantity of lachrymal fluid necessary to keep the eyes normally lubricated.[94] But for a larger production of tears, Steno argues that disturbances in the blood flow – such as the ones caused by strong emotions – were the main cause, since some components of the blood would feel pressured to follow other paths like "the simple and porous tunics of the capillaries present inside the glands."[95] The particles [*partes*] of this humor that leave the blood into the glands, which he calls "serum," "enter with greater speed, as they naturally tend to, so that the speed compensates for the transit through the narrow vessels."[96] Therefore, Steno concludes that the increasing speed of blood filtration alone produces "great abundance of tears."[97]

The speed and flow of blood had also been critical in William Harvey's discovery of the circulation of blood. Harvey decided to calculate the amount of blood ejected at each forceful systole of the heart.[98] His results made him realize that "in a comparatively short space of time the whole of the blood contained in the body must pass

[85] Wharton, *Adenographia*, pp. 181: "Ego existimo esse nervos, præcipuè illos, qui decurrentes per plexum retiformem, in eum, ut dixi, copiosas cerebri humiditates effundunt, ex eóque penu sufficientem oculis materiam miniftrant." Elizabeth Craik, "The Reception of the Hippocratic Treatise *On Glands*" in M. Horstmanshoff, H. King and C. Zittel (eds.), *Blood, Sweat and Tears – The Changing Concepts of Physiology from Antiquity into Early Modern Europe* (Leiden: Brill, 2012), pp. 65-82, esp. 66.

[86] On emotional tears as specific to humans see Steno, *Observationes anatomicae*, p. 92: "et sequeretur, etiam brutis attribuendas lacrymas, quod multis absurdum videtur." (BOP, p. 490). On the brain as the center of the nervous system, an idea held by most Ancient writers, see Vivian Nutton, *Ancient Medicine*, 2nd ed. (New York: Routledge, 2004, 2013), pp. 118, 134, 238-240.

[87] Steno, *Observationes anatomicae*, p. 90: "modò impetuosius profluens lacrymarum nomine venit" (BOP, pp. 488).

[88] Steno, *Observationes anatomicae*, p. 92: "si guttarum magnitudo cum tempore, quo colliguntur, conferatur, nulla hic videbitur difficultas. Nec enim tempus adeo breve, quin per plura vasa tantum humoris affluere possit, quantum ad guttam constituendam requiritur;" (BOP, p. 490).

[89] Wharton, *Adenographia*, p. 134: "Proximo loco inquirendum, est è quibusnam partibus et perquas vias hic humor in glandulas salivales derivetur. Credibile est, è nervoso genere profundi."

[90] Steno, *Observationes anatomicae*, §38, p. 35: "Ex prædictis itaque facilè liquet, arterias glandulis, præter calorem, etiam nutrimentum, et simul salivæ materiam suppeditare." (BOP, p. 449).

[91] Wharton, *Adenographia*, p. 136: "Denique, maior est quantitas materiæ salivalis per has glandulas excretæ, quam facile credas ab exiguis illis arteriis et venis quæ ad has partes distribuuntur."

[92] Steno, *Observationes anatomicae*, §37, p. 34: "Cum enim eadem celeritate, qua sanguis accedit, in os non influat saliva, poterit mora, quam hæc in fluxu suo trahit, illius celerius affluentis paucitatem compensare." (BOP, p. 449).

[93] Steno, *Observationes anatomicae*, p. 92: "Nec, qui ex oculis emanat, humor, totus in glandulis antea fuit coacervatus." (BOP, p. 490).

[94] Steno, *Observationes anatomicae*, p. 91: "Existimo itaque, manifestum satis esse, illum saltem humorem, qui motui palpebrarum inseruit, ex arterioso sanguine in glandulis secretum per descripta modo vasa adferri." BOP, p. 489).

[95] Steno, *Observationes anatomicae*, p. 94: "eo copiosius per simplices et porosas capillarium intra glandulas existentium tunicas exprimetur serum;" (BOP, p. 491).

[96] Steno, *Observationes anatomicae*, p. 94: "quicquid per alias vias egredi aptum est, ingreditur illas maiori, ac naturaliter solet, celeritate, ut ita viarum angustiam transitus celeritas compenset;" "hi meatus non dilatentur." (BOP, p. 491).

[97] Steno, *Observationes anatomicae*, p. 94: "celeritas majori lacrymarum copiæ producendæ sufficit." (BOP, p. 491).

[98] William Harvey, *Exercitatio anatomica de motu cordis* (Frankfurt, 1628), chapter 9.

through the heart," and so the blood had to be in circulation.[99] However, according to historian Roger French, this quantitative method was very rough, and "far less precise than those of Sanctorius and van Helmont."[100] Yet, the point is that neither Harvey nor Steno were looking for precision in these cases, but only to show the role of quantities in blood circulation.[101] In Steno's case it was the changing speed of the circulation that mattered for the production of tears. Steno went on to explain where exactly in the blood system these changes occurred and how the mind affected it, saying that it involved the muscles around the heart.[102] It was from this early research using quantification and applying notions from mechanics to anatomy that Steno began to study muscle physiology, a topic which would remain central in his future anatomical research.

MECHANISM AND GEOMETRY IN THE MUSCLES, 1662-4

Steno was able to direct his research from the discovery of the salivary duct in the parotid gland to the most relevant topics of anatomy at the time, first to the lymphatic vessels, with the conglobate glands, and then to the circulation of blood – the hot topic of anatomy, still debated at the time.[103] Starting in 1662, Steno began to look at muscle physiology more closely and, in a leap of anatomical mastery, he connected it again to the heart, by arguing that the heart itself was a muscle.[104] As Steno delved more deeply into this new research, his mathematical yearnings continued to grow. Indeed, for Steno, mathematical arguments and concepts represented something deeper than they did for other anatomists. Later that year, in August 1662, Steno wrote a letter to Thomas Bartholin saying that, after he published the *Observationes*, he "had decided to lay down the anatomical knife until more convenient times and to take up again the nearly-cast-away geometer's rod."[105] Such a decision, however, did not move forward. In his own words,

> hardly were my fingers, rid of blood, slightly besprinkled with this very pleasant powder [of geometry] that partly the fairly acid faces of famous gentlemen, partly their unfriendly writings that presented my opinion in a sense different from mine, denied me the happiness desired for a long time so that they imposed on me the necessity to answer and also to return to this bloody task.[106]

These strong words, although unrelated to the rest of the letter, were enough to show where Steno's heart was with respect to mathematics after his successful research on the glands. More importantly, it revealed a previous commitment of Steno's to mathematics for which, he said, "I spent many hours in the past and which I would have treated not as my primary, but as my unique work, if straitened circumstances at home had not so much convinced as forced me to prefer the useful to the pleasant."[107] It is not yet clear what exactly Steno did in the many hours that he worked as a geometer in the past, but his studies in Copenhagen with Jorgen Eleirsen, the headmaster of his Latin school to whom Steno dedicated the treatise on the eye glands, might be the answer.

In May 1663, while travelling through Belgium with Ole Borch (1626-1690) and other friends, Steno met the mathematician Grégoire de Saint-Vincent (1584-1667) when visiting the Jesuit College of Ghent.[108] De Saint-Vincent was an 80-year old Jesuit who became famous for his works on the quadrature of the circle and on mechanics, which might have attracted Steno's interests.[109] By then, Steno was already working on his new

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99 Roger French, *William Harvey's Natural Philosophy* (Cambridge: Cambridge University Press, 1994), p. 90.

100 French, *William Harvey's Natural Philosophy*, p. 92.

101 Bylebyl, "Nutrition, Quantification and Circulation," p. 383.

102 Steno, *Observationes*, pp. 92-97 (BOP, pp. 490-4).

103 In 1666, the physician Michele Lipari in Messina still argued that the pulse did not depend on the circulation of the blood but on vital spirits, see Bertoloni Meli, *Mechanism, Experiment and Disease*, pp. 58, 66. In 1670s France, physicians still gave long lectures against the circulation of the blood, see Guerrini, *The Courtiers' Anatomists*, pp. 207-9. See also Bartholin, *Epistolarum medicinalium centuria III* (Copenhagen, 1667), pp. 308-311: "De sanguinis circulatione dissensus"

104 Steno, *De musculis et glandulis observationum specimen*, p. 22: "Cor vere musculum esse." (BOP, p. 562).

105 Steno to Bartholin, 26 August 1662, in Bartholin, *Epistolarum Medicinalium Centuria IV* (Copenhagen, 1667), p. 103: "Cum pauculas meas luci publicæ exponerem observationes, decreveram, repositio in commodiora tempora cultro Anatomico, Geometricum radium tantum non abjectum resumere." (BOP, p. 511).

106 Steno to Bartholin, 26 August 1662, in Bartholin, *Epistolarum IV*, p. 103: "Sed vix purgati sangvine digiti jucundissimo illo pulvere leviter erant perspersi, cum Virorum Clarissimorum partim minæ satis acerbæ, partis scripta parum amica meamque sententiam sensu non meo proponentia desideratam diu felicitatem mihi inviderent, et ut respondendi, sic quoque ad sanguinarium illud excercitium revertendi imponerent necessitatem." (BOP, p. 511).

107 Steno to Bartholin, 26 August 1662, in Bartholin, *Epistolarum IV*, p. 103: "non paucas olim impendi horas, quodque non ut primarium, sed ut unicum tractassem, nisi angusta domi res utilia jucundis præferenda non tam suasisset, quam imperasset."

108 See H.D. Schepelern (ed.), *Olai Borrichii Itinerarium 1660-1665 : the journal of the Danish polyhistor Ole Borch*, 4 vols. (Copenhagen: Danish Society of Language and Literature, 1983), vol. 2, 26 May 1663: "Colloquium institutum in collegio Patris Societatis Jesus, cum patre à S. Vincentio jam octogenario, sed vivid adhuc, et novum scriptum intra biennium promittente."

109 Geert Vanpaemel, "Jesuit Science in the Spanish Netherlands" in Moderchai Feingold (ed.), *Jesuit Science and the Republic of Letters* (Cambridge, MA, 2003), 389-432, esp. 391-397, 405-406, 418-420.

book, *De musculis et glandulis observationum specimen* (1664).[110] The book, published in 1664 in Copenhagen and Amsterdam, was his first printed work on muscle anatomy.[111]

In *De musculis et glandulis*, Steno relied again on mechanical analogies. For instance, when explaining how the muscles contract, Steno said that "it is not the tendon which contracts but the flesh comprised between the tendinous expansions."[112] To explain it better and, "since an explanation through similar things greatly pleases many people," Steno mentioned a complex pulley that brings structural posts to the ground by men holding ropes.[113] In this example, the men control the machine by each one holding a single cable and pulling it together. In the muscles, the ropes represent the tendons, the weight hooked to the ropes represent the mobile part and the men themselves represent the fleshy fibers. By pulling their ropes together, said Steno, "the men indeed move the weight. Similarly, the contracting fleshy fibers, while they pull the fibers of the tendon move the mobile part." [114] However, Steno did not push this analogy too far, and stated that it was "only a comparison."[115] Steno used a similar mechanical analogy when explaining the motion of the diaphragm, as he compared the abdomen to a pulley.[116]

If the use of mechanical analogies was similar to Steno's previous description of blood filtration on the glands, his geometrical descriptions, however, were much more explicit and served a more intentional purpose in this treatise than in previous ones. In the first part of the treatise, Steno said that most anatomists did not agree on the description of intercostal muscles, because such muscles are difficult to distinguish, although performing the same function together. However, Steno proposed to distinguish them according to "the different angles [they make] with the ribs."[117] Steno suggested that this categorization of the muscles carried an epistemological certainty almost as strong as mathematical certainty, for "the one who will not refuse to examine carefully the angles formed by the back, the ribs, the sternum and the muscles must find a demonstration of these muscles, perhaps not less certain than by mathematics."[118] Further on, after saying that every muscle was composed of fibers and tendons, Steno concluded that the fibers have a very specific disposition, as they "form an oblique parallelogram or the figure of a rhomboid" (fig. 4).[119] After explaining how exactly the fibers and tendons were disposed in this geometrical figure, Steno felt the need to say that "even when dealing with physics, I give mathematical names to physical and not mathematical lines."[120] Steno was alluding to the old epistemological problem of mixed mathematics of whether natural things can be described by means of mathematical entities that do not exist perfectly in nature. Steno, however, felt it was better to "leave these details to mathematicians," and reinforced that both fibers and tendons are composed of fleshy fibers in a different concentration.[121] Thus, Steno's commitment to mathematics was useful to him only in so far as it served the purpose of argumentation in anatomy. Another example comes from a "letter on the anatomy of a ray" to William Piso (1611-1678), included in *De musculis et glandulis*.[122] Piso was an Amsterdam physician famous for his collaboration with the mathematician Georg MacGravius (1610-1644), with whom he wrote a widely-read natural history of Brazil.[123] In this letter, Steno records not only the weights of the parts of the ray, but also comments on the animal's geometric shape, just like he had done with the muscles he was studying.[124]

[110] Steno's first results on the muscles were reported in a letter to Thomas Bartholin from April 30, 1663. His first dissections on the muscles are mentioned in a letter to Bartholin from 26 August 1662. See Bertoloni Meli, "The Collaboration between Anatomists and Mathematicians," pp. 696-697.

[111] The book was only printed in or after June, since it includes one letter sent on the 12 June 1664, in Nicolaus Steno, *De musculis et glandulis* (Copenhagen, 1664), p. 84.

[112] Steno, *De musculis et glandulis*, p. 19: "Qui contrahitur, non tendo est, sed tendinosas inter expansiones comprehensa caro" (BOP, p. 561).

[113] Steno, *De musculis et glandulis*, p. 19: "cum per similia explicatio multis magnopere arrideat" (BOP, p. 561).

[114] Steno, *De musculis et glandulis*, p. 20: "ut enim homines breviores redditi, suas dum simul trahunt chordas, pondus movent; sic carneæ contractæ fibræ, dum tendinis trahunt fibras, mobilem movent partem." (BOP, p. 561).

[115] Steno, *De musculis et glandulis*, p. 20: "Sed cum simile hoc tantum sit, non diutius ipsi immorandum." (BOP, p. 561).

[116] Steno, *De musculis et glandulis*, p. 9: "Nec enim, cum vel maxime tenditur, in rectam extensum est, nec, circa qvam moveatur, trochleam habet (nisi abdominis hic volueris nominanda contenta)" (BOP, p. 555).

[117] Steno, *De musculis et glandulis*, p. 6: "angulos cum costis constituunt diversos" (BOP, p. 553).

[118] Steno, *De musculis et glandulis*, pp. 9-10: "Sed his missis quorundam musculorum describam in respiratione usum, quorum demonstrationem Mathematica forte non minus certam non poterit non invenire, qui, quos dorsum, costæ, sternum, musculi inter se conficiunt, angulos attente examinare non recusaverit." (BOP, p. 555).

[119] Steno, *De musculis et glandulis*, p. 15: "Ejusdem ordinis fibræ in eodem plano sunt, et parallelogrammum obliquangulum, seu rhomboideam exhibent figuram." (BOP, p. 559).

[120] Steno, *De musculis et glandulis*, pp. 15-16: "Rem Physicam proponenti venia detur, si Mathematicis nominibus Physicas, non Mathematicas, designem lineas." (BOP, p. 559).

[121] Steno, *De musculis et glandulis*, p. 16: "Sed illam Mathematicis relinqvamus ἀκρίβειαν." (BOP, p. 559).

[122] Steno, *De musculis et glandulis*, p. 48: "De anatome rajæ epistola."

[123] In Leiden, Borch met MacGravius' brother, who mentioned a new book by Georg on "his mathematical speculations," apparently also edited by Piso. See *Olai Borrichii Itinerarium*, vol. 1, 27 April 1661, p. 115.

[124] Steno, *De musculis*, p. 15, 42 (BOP, p. 559, 580).

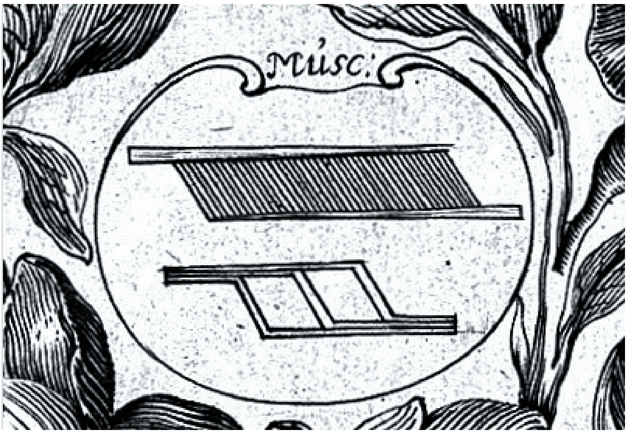

Figure 4. Geometrical representation of the muscles in the cover of Steno, *De musculis et glandulis* (Copenhagen, 1664). Courtesy of Wellcome Collection.

But Steno did not add a reason as to why he made these mathematical interventions. It was as if these approaches had already become regular and normal for him.

MATHEMATICS AND NICOLAUS STENO'S ARRIVAL IN ITALY

Considering that Steno had already explored mathematical methods for some time, it is fair to ask what he might have been looking for when he went to Italy for the first time, in the spring of 1666. Before his arrival in Italy, Steno did not publish any other book. His famous dissection of the brain in 1665 in Paris only appeared in print four years later. And there are not many other writings from Steno's sojourn in France, although several scholars like Jan Swammerdam (1637-1680) and André Graindorge (1616-1676), wrote about their joint activities in Paris.[125] However, the possibility that Steno interacted with French mathematicians like Gilles Personne de Roberval and Adrien Auzout, both of whom had collaborated with the anatomist Jean Pecquet, should not be disregarded. Steno's friendship with Melchisedec Thévenot (1620-1692), whose circles brought together some of the founding members of the *Académie des Sciences de France*, suggests that Steno might have shared his geometrical interests with them in the critical years before the publication of his seminal *Elementorum myologiæ specimen*.[126] Steno expanded his mathematical approach in that book, a full treatise on the mathematical elements of myology, where he explained better the rhomboid structure of muscles.

The book also "call[ed] upon the testimony of Vincenzo Viviani, mathematician of the most serene Grand Duke, who was present as a keen observer of these facts and of others contained in the present book."[127] It could be that Steno went to Italy in search of the mathematical and experimental legacy of Galileo, Viviani and Borelli. But Steno never mentioned them in his anatomical works, even when writing on mathematics. And Steno's mention of Galileo in his student notebook from 1659 in Copenhagen is very short, compared to his notes on the writings of Athanasius Kircher, Jean Pecquet and Pierre Gassendi.[128] This is not to say that Steno was not influenced by the school of Galileo later on in Florence. Troels Kardel rightly points out the striking differences between the *De musculis et glandulis* (Copenhagen, 1664) and the *Elementorum myologiæ specimen* (Florence, 1667), especially the role of images. And Domenico Bertoloni Meli argues that the latter's life-size images carried demonstrative power for Steno in the same way as accounts of experiments carried for Galileo.[129] Bertoloni Meli also points out that Steno's use of the terms *inaequaliter aequaliter* to describe the disposition of fibers between tendons, resembles the famous Galileo description of the uniformly accelerated motion.[130] Thus, whereas the school of Galileo played an important role in shaping Steno's later writings, it does not seem to have been at the heart of the matter earlier on. In fact, to understand the factors that led Steno and other anatomists to mathematics, it is perhaps useful to look away from the shadow of Galileo, Descartes and other great names of seventeenth-century science.[131]

Finally, even though Steno did not mention it, he was likely aware of the Italian school of mathematics. The intellectual circles he frequented in the Netherlands and France were well informed of the scientific developments of Italy, often due to a competitive spirit. An example to be explored further is the race for the lost manuscripts of Apollonius' conics, led by Steno's professor of mathematics Jacob Golius in Leiden and by Borelli in Florence

[125] Scherz's biography, in BOP, pp. 131-161

[126] The *Académie* was founded within a year of Steno's sojourn. See Guerrini, *The Courtiers' Anatomists*, pp. 85-88; Nicholas Dew, *Orientalism in Louis XIV's France* (Oxford: Oxford University Press, 2009), pp. 89-92.

[127] Steno, *Elementorum myologiæ specimen*, p. 119: "amicissimum mihi *Vincentium Viviani,* Serenissimi Magni Ducis Mathematicum, testem appello" (BOP, 739).

[128] Ziggelaar, *Chaos*, pp. 301-2.

[129] Bertoloni Meli, "The Collaboration between Anatomists and Mathematicians," pp. 705-706.

[130] Bertoloni Meli, "The Collaboration between Anatomists and Mathematicians," p. 706.

[131] Steno's mentors were generally critics of Cartesian anatomy. For Bartholin on Descartes see Jesper Andersen, *Thomas Bartholin: Lægen & anatomen* (Copenhagen: FADL's Forlag, 2017), pp. 52-62; for Sylvius and Van Horne see Ragland, "Mechanism, the Senses, and Reason."

around 1660.[132] When Steno visited Borelli in his first months in Florence, the latter was already working on his *De motu animalium*, published posthumously.[133] Yet, the absence of all these references in Steno's writings only makes him a more interesting character, and speaks to the larger role of mathematics and its broader influences in Steno's career before arriving in Italy.

CONCLUSION

If anything, this article shows that Steno's interest in mathematics had been in his mind at least since his interaction with Jorgen Eilersen as a young student in Denmark. In Leiden, Steno's first publications on the glands made use of mathematical ideas, not just with mechanical analogies, but also with the measuring of weights of the parotid glands and the uses of the concepts of lubrication, speed flow to explain the production of salivary and lachrymal fluids. Later on, in *De musculis et glandulis*, Steno continued to rely on mechanical analogies while at the same time moving to a deeper use of geometry, by describing the muscles with the geometrical figure of a rhomboid. Steno's attraction to mathematics in his early anatomical research thus becomes an important case of how an anatomist transferred arguments and methods from geometry and mechanics into anatomy and the life sciences, and sheds light on the growing influence of the mixed mathematics and physics in the history of science up to modern times.

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[132] Luigi Guerrini, "Matematica ed Erudizione. Giovani Alfonso Borelli e l'Edizione Fiorentina dei Libri V, VI e VII delle *Coniche* di Apollonio di Perga" *Nuncius* 14 (1999), pp. 505-568.

[133] In a letter to Marcello Malpighi from 1667, Giovanni Battista Capucci mentions Borelli's work and its similarity to Steno's *Elementorum myologiæ specimen*, see Capucci to Malpighi, 25 July 1667, in Adelmann, *The Correspondence of Marcello Malpighi*, vol. 1, p. 352: "[Borelli] ha promesso a' nostri amici di colà in breve tempo il suo libro de motu animalium, del qual argomento, Dio voglia, ch'il Sr. Stenone non se n'abbia tolto il meglio, così come ha prevenuto in publicarlo, mentre questo come Vostra Signoria Eccellentissima dice anche procede con principij geometrici. Non bisogna publicar l'idee di belle cose, e tirarne a lungo la composizione, e la stampa, sé non vogliono esser involate."

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Abstract. In Part One of the *Specimen of Elements of Myology,* a book in three parts published in Florence 1667, Nicolaus Steno described the changes taking place between muscle relaxation and contraction in a two-stage geometrical model based on anatomical observations in man and animals. The 'new myology' was rejected by G.A. Borelli in 1680 and outright ridiculed by J. Bernoulli in 1694. The anatomical correctness and predictive value was rightfully acknowledged only towards the Millennium. In Part Two, the *Canis …,* Steno gave a detailed anatomical description of a giant shark's head with focus on the likeness of its teeth and the so-called tongue stones, or "glossopetrae", dug from the ground. Steno conjectured that remnants from sharks living in the past had become fossils due to chemical processes through interaction with the surrounding sediments at the bottom of the sea, presuming that the finding areas had been sea-covered. From studies in Part Three of reproductive organs in mammals, viviparous ray-fish and shark, he concluded that the so-called female testicles in women and mammals are analogous with ovaries of oviparous animals and should therefore be named accordingly. Two years later in the *Prodromus De Solido intra Solidum,* Steno described the transformation over time of sedimentary landscapes in Tuscany, and how crystals grow by accretion to the surface of entities derived from limpid sea-water or freshwater in caves. These are studies of time-related transformations of solids in organic and inorganic materials. However, such processes could not be documented by visual observation, since changes go too quickly in muscles, in the case of the landscapes because the transformations took place in the past. Thus, Steno and contemporaries put forward hypotheses on such hidden processes that were only gradually corroborated when fitting into a cluster of evidence. His considerations on crystal growth may have been triggered by an interest as a physician to know how saliva, gall and kidney stones are formed. Likewise, considerations on sharks' replacement of their teeth could extend knowledge on dentition to bring a better cure for those who complain of being toothless. He emphasized the importance of mathematical methods to describe processes in the human body and cited from Galileo, *Discourse on Bodies in Water* (1612), in which physics outweighs Aristotelian rules to explain the interaction of solids and solvents. Likewise, Steno's 'New Myology' was a showdown against an Aristotelean physical dogma from *Physics* VII: *everything which moves is moved by another*, which excluded fibre shortening in muscles and blinded researchers on muscle contraction for generations after Steno.

[1] This paper was written during the height of the Covid-19 epidemics in 2020 based on impressions from seminars in 2019 in Copenhagen, San Francisco, and most of all, the conference *Galilean Foundation for a Solid Earth* in Florence. All references are numbered in square brackets and listed at the end of the paper.

Keywords: Nicolaus Steno, History of Geology, History of Biology, Geometrical Models.

INTRODUCTION

How well then everything fits together!
How unanimously they come together in agreement.[2]

This paper contributes reflections on Steno's 'New Myology', published 1667 in *Specimen of Elements of Myology* [2] and draws parallels to the *Prodromus to a Dissertation on a Solid Naturally Contained Within a Solid* [3] that followed only two years later, and to other writings showing his interest in body-liquids in biology and the solute-solvent relation in geology. It will be shown that Steno took an anti-Aristotelean stand in his biological as well as in his geological research.

In his research on muscle Steno added a time relation to structural transformations making observations measurable in a meaningful way as devised by Galileo already recognized in his time.[3] As a student in Copenhagen Steno excerpted text from Galileo's, *Sidereus Nuncius* (1610), in the CHAOS-Manuscript (1659) ([4] pp. 301-302). In the *Prodromus* ([1] pp. 169, 802) he quoted essentials from Galileo's *Discourse on Bodies in Water* (1612) [5] in which Galileo expressed a critical position to Aristotelian explanations of physical phenomena. Along the same line, Steno's 'New Myology' was a showdown against an Aristotelean physical dogma that precluded fibre shortening in muscles as earlier researched and described in the following section ([17] p. 40).

1. *SPECIMEN OF ELEMENTS OF MYOLOGY*, A BOOK IN THREE PARTS.

Part one, the *Specimen,* is entitled as the whole book. In the introduction the author expressed that he:

> *wished to demonstrate in this dissertation that unless myology becomes a part of mathematics, the parts of muscles cannot be distinctly designated, nor their movement successfully studied. And why should we not give to the muscles what astronomers give to the sky, what geographers to the earth, and, to take an example from microcosm, what writers on optics concede to the eyes.* ([1], pp. 187, 651)

Steno leans on a text by Galileo, *Il saggiatore* (1623)

> *Philosophy is written in this grand book, the universe, which stands continually open to our gaze. But the book cannot be understood unless one first learns to comprehend the language and read the letters in which it is composed. It is written in the language of mathematics, and its characters are triangles, circles and others geometric figures without which it is humanly impossible to understand a single word of it; without these, one wanders about in a dark labyrinth.* ([5], p. 207)

In the *Specimen,* a geometrical analysis of the muscle contraction is based on anatomical dissections in animals and humans with the inner structure illustrated by three wood-block prints, displayed as when cut along the length of the muscle from tendon to tendon. Just one cut in a leg of a rabbit was enough for Steno to realize the shortcomings of the ancient system and then make a three-dimensional geometrical model in two stages, relaxation and contraction (Fig. 1).

Two elements were essential to make a model of muscle contraction, first the feather-like, or pennate *structure* of skeletal muscle. He saw it two-dimensionally in a cut along the fibers and visualized it as a parallelepiped in three dimensions in three wood-block prints ([1], pp. 677-686) altogether specified from anatomical dissections in 44 *Definitions* ([1], pp. 654-664). The *functional* properties as the result of *shortening of muscle fibres* was detailed in five *Suppositions* ([1], pp. 664). A geometric deduction in six *Lemmas,* help sentences, allowed him in the *Proposition* to conclude that muscles in action make a swelling of muscle *even without an increased volume*. Therefore, the swelling as seen and felt during contraction is not an argument for volume increase by 'animal spirits' as had been held since antiquity ([1], p. 653). He rejected the so-called 'animal spirits' as an alleged instrument of action within the body when an acting agent was in demand and shunned speculative stereotypes. Early he wrote, "Reasoning deprived of the work of the senses did not find the paths carrying the saliva into the mouth" ([1], p. 428).

Considering the contraction process, Steno mentions some areas where knowledge on muscle was lacking,

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[2] 'Qvam bene itaqve conveniunt omnia! Qvam unanimi consensu inter se conspirant!', quotation p. 726 in T. Kardel, P. Maquet, eds., *Nicolaus Steno, Biography and Original Papers of a 17th Century Scientist*, 2nd edition, Heidelberg, Springer, **2018** https://doi.org/10.1007/978-3-662-55047-2_4 ([1], p. 726).

[3] 'When Cardinal Leopold sent Steno's Myology to Michel Angelo Ricci, the Roman erudite thanked him on May 30, 1667 and said he was enthused by the zeal, the gift of observation, and the genius of the Danish researcher and praised his endeavours in the spirit of Galileo' ([1], p. 167).

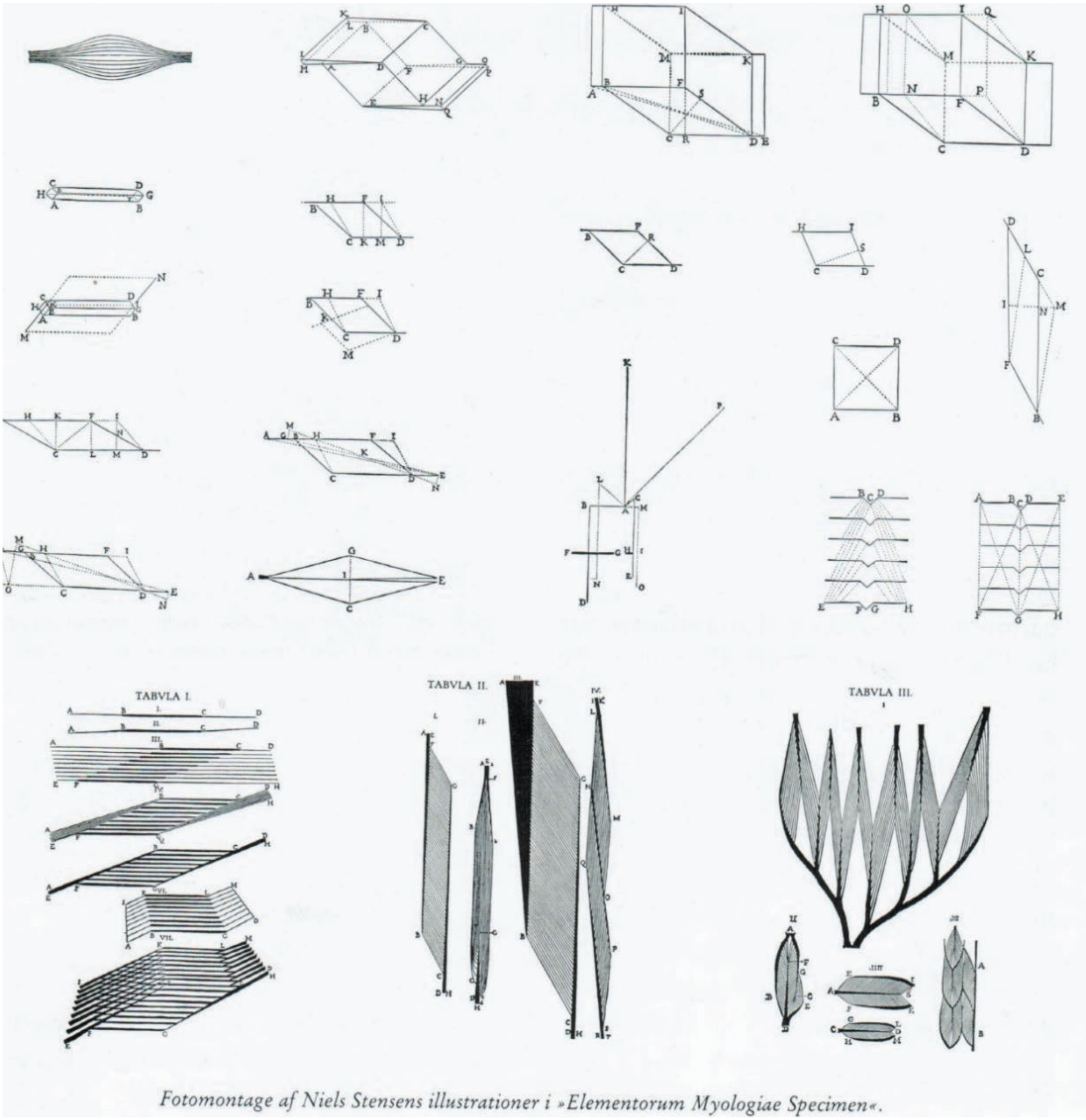


Figure 1. Illustrations brought together from the *Specimen of Myology* by Harald Moe ([6], p. 100). The upper left sketch shows what Steno calls the ancient structure of muscle, and thereafter what he proposes as the new structure of muscle. Then sketches of a model in relaxation (solid lines) and action (stippled lines), when fibres of the muscle shorten. In the lower row, three wood-block prints show: Tabula I, the inner structure of the typical feather-like, or pennate, muscle with the lower drawings in true perspective; Tabula II, the inner structure of gastrocnemius, biceps brachii, semimembranosus and semitendinosus muscles; Tabula III shows the deltoid and masseter muscles, all from dissections in humans, and muscles from claw of lobster (abductor and adductor) and from fish. In the lower row, the anatomical base for Steno's model of muscle contraction as drawn in the functional sketches above.

among them 'What is the movement of the fluid?' ([1], p. 695). This is even today an object of investigation being pressure dependent.

Steno developed his muscle theory in the early 1660's during doctoral studies on glands in Leiden. He was at the same time trained in brain anatomy by Frans dele Boë

Figure 2. Muscles and tendons of the human shoulder and arm as described by Johannes Van Horne and illustrated in colour by Marten Sagemolen in Leiden, appr. 1660 [7].

Sylvius and in anatomy of the muscles by Johannes Van Horne. The magnificent atlas of the human muscle system by the latter with colour drawings by Marten Sagemolen [7] was ready for print but went in oblivion after Van Horne's death in 1670. The drawings were only recently rediscovered to reveal a masterpiece in colour (Fig. 2). [4]

Optimally trained for the task Steno realized that the ancient system of the brain's motor control by 'animal spirits' carried through hollow nerves to enact muscular contraction by inflation as described by Descartes 1662 in the posthumous, *Treaty on Man*[5] [8] lacked anatomical correlates. Alongside, Jan Swammerdam, a fellow student and friend of Steno's, made experiments that showed no volume increase during contraction in frog muscles kept within a restricted space. Swammerdam's results countered muscle contraction by inflation but remained unpublished until 1737 [9]. A preliminary version of Steno's myology was published in the *Specimen of Observation on Muscles and Glands,* in Amsterdam and in Copenhagen, 1664 in which he also emphasized that "the heart is actually a muscle", followed up with a categorical statement on,

> *What the Substance of the Heart is* Not: *The heart is no longer a substance of its own kind and, therefore, it is neither the seat of a certain substance like fire, innate heat, the soul, nor the generator of a certain humour, like the blood, nor the producer of some spirits, e.g. vital spirits.* ([1], p. 565)

In the *Discourse on the Anatomy of the Brain* held in Paris 1665 and published four years later, Steno distanced himself from Descartes' and Willis's speculative approaches to brain anatomy. When in Paris, Steno demonstrated the "new myology" as evidenced by the Graindorge letters to Huët [10]. He showed the new system for travelling English scientists at their sojourn in Montpellier. William Croone had also published a book on muscle contraction in 1664. Unlike Steno, Croone explained and illustrated the contraction of muscle based on inflation like Descartes. On their encounter Nayler concludes: '… arguments adduced by Steno seem to have had no impact on Croone's thinking' [11]. For a long time Croone was the influential secretary of the Royal Society. He favoured Borelli's work in 1680 and never accepted fibre shortening [12]. In Wilson's account: 'Poor Croone must have felt rather crushed when he finished reading this critical discussion by Steno. Those features of his theory which were not wrong were at best speculative' [13].

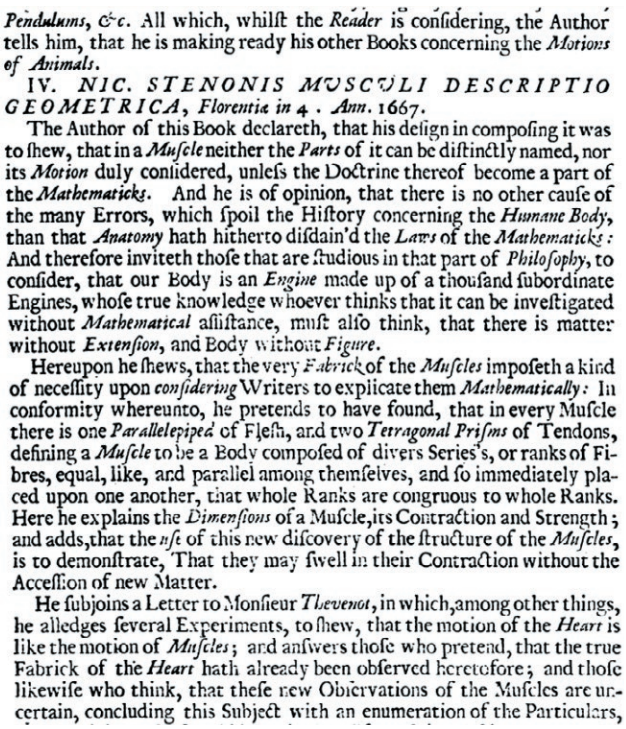
Met by interest, Steno's work on muscle received limited early support. Yet, with recommendations by his mentor Thomas Bartholin and his benefactor in Paris, Melchisédek Thévenot, Steno was well received in Florence, as remarked in a recently recovered letter by Prince Leopold, the Principal of the Cimento Academy:

> [We recently received two guests among whom] *the Danish Anatomist Mr. Stenone, young of age but distinguished in his profession with every sort of erudition, and a good geometrician which will greatly help him in his profession, and the true type of modesty.*[6]

[4] J.-F. Vincent, C. Perrot. *Johannes Van Horne and Marten Sagemolen's myology.* – 31 Aug. 2016. Trad. Oct. 2016 http://www.biusante.parisdescartes.fr/ressources/pdf/van-horne_en.pdf

[5] R. Des Cartes, *De Homine figuris et latinitate donatus a Florentio Schuyl*, Leiden, Moyardus and Leffen, **1662**. Title page with the translator's dedication to the erudite King of Denmark and Norway in (10) T. Kardel, Steno – Life, Science, Philosophy. *Acta historica scientiarum naturalium et medicinalium*, *44*, Copenhagen 1994, p. 27 (11).

[6] Leopoldo de' Medici: Letter in Italian, dated 1666 (April 27?) in Firenze. Royal Danish Library, Manuscript Collection, Shelf Mark: Acc.


Pendulums, &c. All which, whilſt the *Reader* is conſidering, the Author tells him, that he is making ready his other Books concerning the *Motions of Animals*.

IV. *NIC. STENONIS MVSCVLI DESCRIPTIO GEOMETRICA*, *Florentiæ in* 4. *Ann.* 1667.

The Author of this Book declareth, that his deſign in compoſing it was to ſhew, that in a *Muſcle* neither the *Parts* of it can be diſtinctly named, nor its *Motion* duly conſidered, unleſs the Doctrine thereof become a part of the *Mathematicks*. And he is of opinion, that there is no other cauſe of the many Errors, which ſpoil the Hiſtory concerning the *Humane Body*, than that *Anatomy* hath hitherto diſdain'd the *Laws* of the *Mathematicks*: And therefore inviteth thoſe that are ſtudious in that part of *Philoſophy*, to conſider, that our Body is an *Engine* made up of a thouſand ſubordinate Engines, whoſe true knowledge whoever thinks that it can be inveſtigated without *Mathematical* aſſiſtance, muſt alſo think, that there is matter without *Extenſion*, and Body without *Figure*.

Hereupon he ſhews, that the very *Fabrick* of the *Muſcles* impoſeth a kind of neceſſity upon *conſidering* Writers to explicate them *Mathematically*: In conformity whereunto, he pretends to have found, that in every Muſcle there is one *Parallelepiped* of Fleſh, and two *Tetragonal Priſms* of Tendons, defining a *Muſcle* to be a Body compoſed of divers Series's, or ranks of Fibres, equal, like, and parallel among themſelves, and ſo immediately placed upon one another, that whole Ranks are congruous to whole Ranks. Here he explains the *Dimenſions* of a Muſcle, its Contraction and Strength; and adds, that the *uſe* of this new diſcovery of the ſtructure of the *Muſcles*, is to demonſtrate, That they may ſwell in their Contraction without the Acceſſion of new Matter.

He ſubjoins a Letter to Monſieur *Thevenot*, in which, among other things, he alledges ſeveral Experiments, to ſhew, that the motion of the *Heart* is like the motion of *Muſcles*; and anſwers thoſe who pretend, that the true Fabrick of the *Heart* hath already been obſerved heretofore; and thoſe likewiſe who think, that theſe new Obſervations of the Muſcles are uncertain, concluding this Subject with an enumeration of the Particulars,

Figure 3. Part of the review of the *Specimen of Elements of Myology* published in the *Transactions of the Royal Society of London*, in 1667/68 [14].

But he also anticipated criticism as reflected in the *Specimen*:

> *I can imagine that a number of people will stop after the introductory remarks and decide that this new muscle structure is just a new chimera. But I hope that these people will be kind enough to wait until they have read the entire dissertation before expressing their opinion. They will indeed realize that I follow the track of nature closely, presenting nothing unnecessary.* ([1], p. 653)

Unmistakably, Steno's address was intended for Borelli.

The *Specimen* was reviewed in London in the year of publication [14] (Fig. 3).

The reviewer quoted that in a muscle the motion cannot be described without the use of mathematics, and that the same applies to other bodily functions and mentions that a muscle model shaped like a parallelepiped may swell in contraction without the accession of new matter. Thomas Willis illustrated the pennate structure of skeletal muscle like Steno; Willis adhered, however, to the idea of shortening of muscle by expansion from a kind of explosion [15]. Except for Richard Lower, Willis's assistant, Steno did not obtain British support for the new myology. Soon after in Leiden Steno's former teachers, Sylvius and Van Horne, died. The 'new myology' was recorded in Steno's homeland by Thomas Bartholin with an illustration in *Anatomia Renovata*, 1673 ([16], p. 290). But no one at home took up valid research on this topic. When therefore the 'new myology' was rejected by eminent scientists and had no supporters, 'the ancient system' got the upper hand for one more century.

The main objectors were Borelli (*De Motu Animalium,* 1680), Bernoulli (*De Motu Musculorum,* 1694), Boerhaave (*Praelectiones,* 1743) and von Haller (*Elementa Physiologiae,* 1762), the latter observed muscle fibres shortening by microscopy but objected against the pennate structure of muscle [17]. By the end of 18th century Steno's myology disappeared from the scientific literature.

Quotations from Steno and Borelli are like a protracted dialogue on two chief *muscular* systems [18, 19]. Steno presented his *Systema novum musculi* in Florence, 1667 [2]. Borelli rejected the new and defended the ancient system in his *De motu animalium/On the Motion of Animals*, in Rome, 1680 [20]:

On the structure of skeletal muscles:

> S: *I represent a muscle as a collection of motor fibers arranged so that the flesh in the middle forms an oblique parallelepiped and the tendons form two opposite tetragonal prisms.* (1, p. 653)
> B: *One must conceive the muscular fibres as a series of small machines of porous or rhomboidal shape like a chain made of rhombs of filaments.* ([20], p. 119)
> *Such single muscles are not seen normally and do not act in the way those famous authors think they do.* ([20], p. 13)

On contraction:

> S: *When a muscle contracts, its different motor fibres shorten.* ([1], p. 690)
> B: *Muscles do not contract by condensing the length of their fibres and bringing closer together their extremities, but their hardness and tightening results from swelling.* ([20], p. 217)

On the relation between heart and skeletal muscles:

> S: *The structure of the motor fiber in the heart and in the muscle is the same: thus the phenomena of movement in the motor fiber which are manifest to our senses and are seen in the muscle are the same in the heart.* ([1], p. 690)

2019/54. http://www5.kb.dk/manus/vmanus/2011/dec/ha/object254119/da/. The letter was offered for sale by www.historyforsale.com and found there in a google-search on checking the year when Prince Leopold became a cardinal. The letter was purchased via www.amazon.com and donated to the Royal National Library in Copenhagen in 2019.

B: *The first and indirect cause of the motion of the heart seems to be different from that of the movement of the muscles of the limbs.* ([20], p. 282)

On the action of the heart:

S: *In a muscle as well as in the heart there is to be observed one and the same action, that is the contraction of the fleshy part. When the fibres of the heart are shortened … they raise the bottom a little towards the basis and consequently the heart becomes shorter and also rounder.* ([1], p. 566)
B: *The fibres of the heart are not aimed by Nature at pulling and bringing their extremities closer together. In contracting the fibres swell and decrease the cavity. In so doing they squeeze out the blood in it like a press.* ([20], p. 250)

A dialogue along these lines must have taken place between Steno and Borelli in 1666 when Steno was preparing the *Specimen* and before Borelli left Florence for good. ([20], pp. 237-240)

In a still unpublished thesis from 1993 on the history of muscle contraction in the 17th century Margaret A. Nayler concludes on Borelli:

Although microscopic observations were doubtfully supportive of a compartmentalized muscle fibre, they were not conclusive, and the fact that working models could be constructed to demonstrate that inflated bladders could lift large weights doubtless added to the probability that Borelli's mechanism offered an acceptable explanation. How this mechanism could explain muscle contracting strongly without a change in length, or contracting with variable strength, given the apparently tenuous link between the proposed chemical reaction and the 'force' developed, are just some of the issues which Borelli failed to explore [11].

The pennate muscle structure was practically forgotten and only rediscovered in 1981 by P. W. Brand et al., American orthopaedic surgeons, when making anatomical dissections to improve techniques for tendon repair. (21) Anatomical studies were soon made useful in computer simulations of muscle action. While considered to be perhaps his weakest work, arguments were presented to reappraise the *Specimen* as one of Steno's significant publications and as a significant work in biomechanical science [19].

Evidence in support of Steno's myology was compiled in 1994 from anatomical and overview studies and from computer model investigations (Fig. 4).

In addition, ultrasound recordings (made for other purposes) by Chow and co-authors [23] show changes of fibre length and pennation angle during contraction in human gastrocnemius muscle that match the pennate model proposed by Steno ([1], p. 200). Likewise, the pennate structure of the biceps brachii muscle recorded in healthy volunteers by Pappas and co-authors [24], confirms details and proportions of the inner structure in sagittal ultrasound sections of human biceps brachii muscle illustrated by Steno from anatomical studies in meager dead bodies. ([1], p. 202)

Anatomical studies, computer model simulations, and biomechanical and historical review articles dealing with the unipennate actuator. Studies that recognize Stensen's contribution are marked with an asterisk [*].

Anatomical studies			
Beritoff	1925	Hindlimb	Frog
Kolb	1937	Anterior tibial	Man
Rollhäuser and Wendt	1955	Gastrocnemius	Cat
*Brand et al.	1981	Hand	Man
*An et al.	1981	Elbow	Man
Wickiewicz et al.	1983	Lower limb	Man
Cooney et al.	1984	Thumb	Man
Huijing	1984	Gastrocnemius	Man
Lieber and Blevins	1989	Hindlimb	Rabbit
Heslinga and Huijing	1990	Gastrocnemius	Rat
Friedrich and Brand	1990	Lower limb	Man
*Linscheid et al.	1991	Hand	Man
Spoor et al.	1992	Gastrocnemius	Man
Lieber et al.	1992	Arm	Man
Overview studies			
Pfuhl	1937	Biomechanics	
Benninghoff and Rollhäuser	1952	Biomechanics	
Gans and Bock	1965	Biomechanics	
Alexander	1968	Biomechanics	
*Otten	1988	Biomechanics	
Zajac	1989	Biomechanics	
*Kardel	1990, 1991	Historical	
*Huijing	1991	Biomechanics	
Kaufman et al.	1991	Biomechanics	
Model simulations			
Huijing and Woittiez	1984, 1985	Gastrocnemius	Rat
Woittiez et al.	1984	Gastrocnemius	Rat
*Otten	1985, 1988	Hindlimb	Cat
*Kaufman et al.	1989	Same data as Woittiez et al.	
An et al.	1989	Elbow	Man
Hoy et al.	1990	Lower limb	Man
Mai and Lieber	1990	Hindlimb	Frog
Pandy et al.	1990	Lower body	Man
Pandy and Zajac	1991	Lower body	Man
*Zuurbier and Huijing	1992	Hindlimb	Rat
*Van Leeuwen and Spoor	1992	Gastrocnemius	Man

Figure 4. Anatomical studies, computer model simulations and biomechanical and historical review articles dealing with the unipennate actuator. Studies that recognise Stensen's contribution are marked with an asterisk ([*]: [17], p. 49 and references)

Commentary on Part One, the *Specimen of Myology*: Steno's model is the first display of the inner structure of skeletal muscles *and* its structural changes in two steps, relaxation and contraction, apt for inclusion in present day's computer simulations of human and animal movements. Through centuries it was considered to be incorrect. *Elementorum Myologiae Specimen*, the book-title, is a key to the treatise that concerns those *specimens* of *elements* (pennate structure and fibre shortening) that are essential to describe *myology* (the function of muscle).

Opposed by scientists and academies, though not opposed by any church, Steno stood much alone with a new theory on human and animal motion. On leaving science for religion, he left the new myology undefended, to become rejected by Borelli in 1680, and by Bernoulli in 1694 because it violated a physical axiom quoted by the latter, *everything which moves is moved by another,* from Aristotle, *Physics* VII. This axiom had blinded Steno's contemporaries and would do so for fellows of the Royal Society of London and other eminent scientists way into the 18th century.

An error tag was glued on Steno's myology for much longer.

2. THE CARCHARODON-HEAD DISSECTED

In Part Two of the *Specimen of Elements of Myology*, Steno showed in many details the similarity in shape between glossopetrae and the teeth of a giant shark. It brought evidence for the process of fossilization of remnants of sharks that had lived in an ocean of the past. Direct observation is obviously impossible; only signs in solid material remain and can be used in considerations. In muscle contraction, structural changes go too fast for visual observation, while in the case of fossilization, the process is too slow to be observed directly.

He had at hand the so-called glossopetrae or tongue-stones dug from the ground in Malta and at locations in southern Italy and the teeth in the jaws of a huge shark as described and illustrated in the *Carcharodon-Head Dissected* (1, p. 699). The riddle was to get an idea of the processes taking place in the dead shark's teeth through the action of compounds from the surrounding sediments at the bottom of the sea or after elevation above sea level where 'definite traces of the sea appear in places that are raised several hundreds of feet above sea level' ([1], p. 818).

Observed facts on the fossils and their surrounding soil were set down in 11 arguments under the headline, *Historia* ([1], p. 718). Here are some of them.

3. *In various places, I have seen that the said soil is composed of layers superimposed on each other at an angle to the horizon.*
4. *I have observed in clayey soil, that these layers, which differ in colour from each other, are split apart in several places, and that all the fissures, which are filled with material of one colour, are almost perpendicular to the layers themselves.*
5. *In those soils that I have been able to observe up to now, bodies of different kinds have been concealed in the same soil, sometimes in the harder, and sometimes the softer sort.*
6. *I have observed that the number of these bodies in clay is quite large in the surface but quite small in the soil itself.*

Next follow the *presumed processes* described in six *Conjectures*.

Conjecture 1, *Whether the soil today produces these bodies.*
Since no bodies seem to be produced anew in harder soil, and since in many regions softer soil probably destroys these bodies, we may suspect not without reason, that soil from which bodies resembling parts of animals are dug does not produce these bodies today.

Conjecture 2, *Whether the soil in question has always been of the same firmness.*
The soil would not have been firm when the bodies referred to were produced in it.

Conjecture 3, *Whether it may have been covered with water.*
Since both the configuration of the ground itself and examples from other places [ancient reports on devastating events like earthquakes] *indicate that this soil once had another situation, since it seems* (Steno refers to Conjecture 2) *that the said soil was once less firm, what is to prevent us from ascribing this softness to the waters, and what is more, to believe that the soil, before it changed its site, was covered with waters, whether the waters were exposed to the open air or were covered by the earth's crust?*

Conjecture 4, *Whether this soil may have been mixed up with water.*
That clay and sand are mixed with strongly agitated water is so obvious from the headlong course of torrents through such soils, and from the agitation of waters by the wind, that no further explanation is needed. Nor is it difficult to prove that sand, clay, tufa, and all sorts of solid bodies may be concealed in stagnant water, even the most limpid water.
I have seen my most amiable teacher Borch dissolve a very hard pebble in ordinary water; why then should we not grant to nature what we cannot deny to art?

Conjecture 5, *Whether it may be taken for a sediment of water* ([1], p. 723).
I shall now make clear the ways in which sediments could have been deposited, so that these matters may in fact be more readily understood.

Steno argues that since water can dissolve solid material, the opposite – that is secretion of solid material from limpid water - may take place. Clear liquids containing solids had been a theme already in Steno's early research on glands and saliva, on tears, on the fluid surrounding the chick in the egg, and it was mentioned six times on amnion fluid in his report on the dissections of various viviparous animals. ([1], pp. 439, 445, 458, 459, 508, 636, 751)

Late in Conjecture 5 of the manuscript used for printing the *Canis Carchariae*, a sign [+ … +] tells that a text insertion in a glued-in sheet should be made here – apparently a comment written later than the surrounding text (Fig. 5; in the following quote the text from "How well then everything fits together!" to "a sediment from water?"):

Such are the various ways in which solids may be precipitated from a fluid, nay more, fluid from fluid (as may easily be shown of those fluids which form the atmosphere);

if the layers in our soil have not been formed in all these ways, it is certain that they could have been formed in such ways. But whatever the exact way in which solids are separated from fluids, they appear either in the form of powder, as in the case of metals precipitated from acids, or as coagulated material, whether it be softer, as in blood where it is fibrous, in milk where it is cheesy, in May dew and rain water where it is a viscous sediment or whether it be harder, like tartar in wine, crystals in salt water, and stony crusts in various springs. It is clear from this that crusts could have hardened out of the most transparent waters, crusts of varying consistency, crammed full indeed with minerals of various kinds.

How well then everything fits together! How unanimously they come together in agreement. We find the position of the soil suited to its having been able to hold waters; we know that both powdered soil and the elements of the said soil could have been mixed with the waters; we do not ignore the ways in which they could have both entered and separated from those waters, nay rather we pay close attention to the variety of layers in the soil itself. Why then is it impossible for this soil to have been a sediment from water?

Let those for whom it is not enough go into underground grottos from which stones were once quarried, and they will observe new rock forming in place of the rock that was removed, nay more, they will perceive stone icicles, formed from bodies secreted by atmospheric fluid, hanging from the vaults: these icicles, hollow inside and made of many cylindrical lamellae, receive neither water nor rock from the vaults, this is not only indicated but also proved by the structure of the lamellae.

The reason for the author's outspoken delight expressed here is presumably what was written in the previous paragraph, which deals with the author's preconception of solid precipitations from *limpid water*. What follows is an explanation of what comes together in agreement with the answer given in the sentences that follow: 'We find …; We know …; We do not ignore …'; concluding: 'Why then is it impossible …? A question to those holding solid precipitations from limpid water impossible.

Conjecture 6, *Whether bodies dug from the ground and resembling parts of animals should be considered parts of animals.*

In this, the last conjecture, the overall conclusion of Part Two on the fossilisation of remains of live material is typical for Steno's way of arguing:

Since the bodies resembling parts of animals that are dug from the ground can be considered to be parts of animals, since the shape of tongue stones resembles the teeth of a shark as one egg resembles another, since neither their number nor their position in the earth argues against it, it seems to me that those who assert that large tongue stones are the teeth of a shark are not far from the truth ([1], p. 731).

Hsu has argued that Steno in his six conjectures presented arguments on bodies resembling parts of animals as a plaintiff would do to win a case [25]. I do agree that the inquiry in conjecture 5 resembles arguments in a legal case, but would rather say that Steno in the concluding conjecture 6 made himself the judgment of the 'case'.

The late Martin Brasier in his last paper discussed Steno vis-a-vis a vocal critic of the biological origin of fossil shells, Martin Lister [26]. Brasier pointed out that in a 1673 publication Lister argues in favour of the biological origin of some echinoderm fossils based on taphonomic[7] criteria as "the earliest known example of taphonomic reasoning in a scientific paper." As commented by Alan Cutler:

Steno had previously published taphonomic observations in both *Canis* (1667) and *De Solido* (1669). In Conjectures 1 and 2 (see above), Steno addresses the question of whether shells and tongue stones are preserved animal remains, or if they grew in-situ due to plastic forces in the earth. He uses the quality of preservation of shells including their lack of distortion in hard versus soft ground matrix to argue against in-situ origin. In Conjecture 6, he briefly discusses fragmentation, burial, and diagenesis of fossil remains. In *De Solido* ([1], pp. 776-777), Steno adds to these ideas, describing different modes of preservation of shells (original material, molds and casts, permineralization), For one specimen he uses his observations to deduce its taphonomic history, "it is possible to conclude with certainty that the shell had been left upon the land by the sea, covered up again by a new deposit and abandoned by the sea" ([1], p. 279).

Though Steno's taphonomic ideas remained undeveloped, they were clearly an important element of his reasoning.

It is worth noticing that Steno made considerations on solid material mixed in water already in his first academic dissertation, *On Hot Springs* in 1660 ([1], p. 411). Yamada has drawn attention to contemporary considerations by Robert Boyle and Robert Hooke. Moreover, Yamada finds remarks in the CHAOS-manuscript being precursors of Steno's later research [27].

Steno had an additional motive for the study of the nature of teeth, that

ignorance of their nature hitherto has meant that the cure of almost all sicknesses affecting teeth is left only to chance.

[7] Taphonomy is the study of how organisms decay and become fossilized.

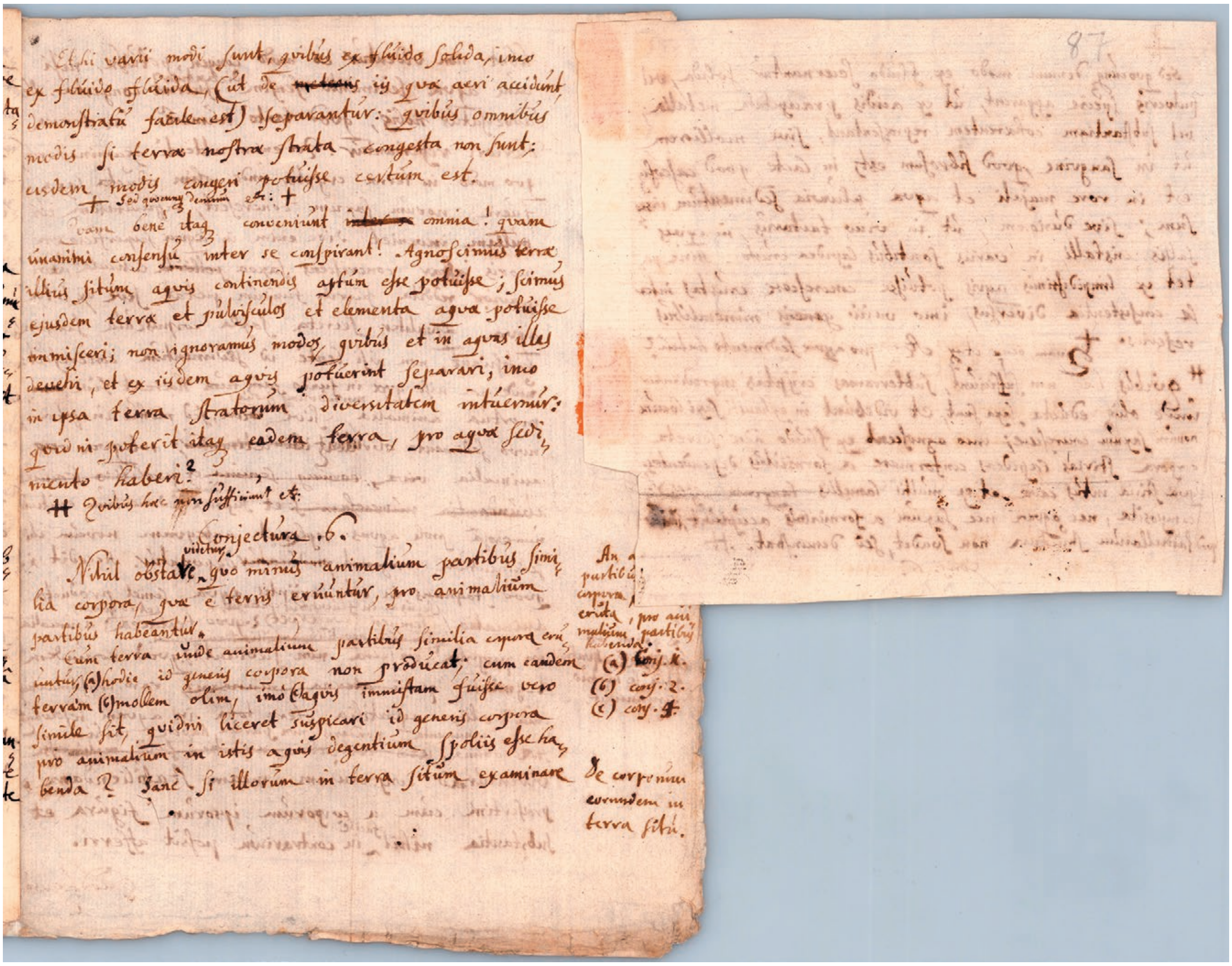


Figure 5. Near the end of Conjecture 5 in the printer's manuscript of *Canis carchariae*, the sign + ... + indicates where to make an insertion from a glued-in sheet. See Fig. 6 for the recto of the glued-in sheet. Illustrations by the Royal National Library, Copenhagen, reproduced with permission.

Who can stop tooth decay once it has begun? Who can lighten their pains? Who can give a clear explanation of the symptoms of teething, or cure it as desired? But if we had a clear idea of their substance, and if we but could make comparisons with other substances, then I do not doubt that we might find a better cure for so many sicknesses, and that the number of those who complain of being toothless would be much less. ([1], p. 717)

Commentary on Part Two: Steno inferred unobservable processes producing structural changes in the teeth of once-living sharks as they became fossils by analogizing particulars that he had observed on the resolution of solid material to and from limpid water. Being merely hypothetical, the live origin of fossils proposed in the *Carcharodon-Head Dissected,* like the muscle model proposed in Part One, came under attack. Both proposals went to oblivion and were rediscovered in later centuries as exemplified by Cutler ([28], pp. 73, 169).

The quote, "it all fits together" [1], seems to indicate the fulfilment of Steno's preconception of solid precipitations from limpid water.

3. DISSECTION OF A DOGFISH

The Grand Duke provided another shark for dissection by Steno in Pisa. *Historia dissecti piscis ex canum* is the third, of the three treatises published jointly in Florence in 1667. The so-called dogfish was a female *Scymnus lichia* in which Steno found in the oviducts an outer membrane, *chorion*, and an inner membrane, *amnion*, and bodies, "considered as eggs in which there was not yet signs of a foetus" ([1], pp. 733-738). He determined that it was a viviparous fish, like two female ray-fishes he earlier had studied in Copenhagen ([1], p. 585). He had "no longer doubts that the [so-called] testicles of females are analogous to ovaries," and stated this will "correct this error by which people believe that the genitals of females are analogous to the genitals of men". Until then ovaries of mammals, women included, had been categorized as "female testicles". Since then they were categorized as analogous with organs of egg laying animals and named accordingly.

Steno examined the shark's internal genitals by making moulds of the oviducts in order to study the mucosa:

> (…) *a parallel structure of nipples appeared most elegantly for the same reason that shapeless wax poured in plaster moulds, when hardened, represents the shape of the mould once the plaster has been removed.* ([1], p. 600, figs. III and IIII).

The moulding technique must have been known to Steno from his father's goldsmith's workshop ([29], p. 132). He later used what Stephen J. Gould called 'the principle of moulding' to determine the relative age of interacting geological items in the *Prodromus* [30].

Steno converted to Catholicism in November 1667 during an active period of research ([1], p. 220).

The book in three parts, the *Specimen of Elements of Myology,* covers pioneering research based on observations and reflections on issues now framed as biology and geology. His conjectures had their origin in incidental observations that in a Galilean sense made further observations measurable for testing in models.

Jens Morten Hansen has assessed the criteria Steno used to obtain certainty on conclusions on unobservable events in the past [31].

Raphaële Andrault [32] categorized Steno's method in research on muscle as the hypothetico-deductive method.

These are opinions on which I can only agree based on my earlier assessment ([39], pp. 96-97). Moreover, in Galileo's *Discorso* (1612) and in Steno's *Canis carchariae dissectum caput* of 1667 (Conjectura 1: [1]), are found the same uncommon marker of the method:

> *verisimile* in Galileo: 'Il discorso, e l'esperienza hanno veramente tanto del probabile , e del verisimile, che maraviglia non sarebbe, se molti persusi da una certa prima apparenza, gli prestassero il loro assenso: tuttavia io credo di potere scoprire, come non mancano di fallacia. / And truly the reasoning and the experiment have so much probability and verisimilitude that it would be no wonder if many, persuaded by a first appearance of [truth], should lend their assent to this; yet I can believe I can show no lack of fallacies' ([35], p. 80).

> *verosimiliter* in Steno: 'Cum itaqve in duriori terra nulla de novo produci videantur corpora; cum terra mollior eadem corpora multis in locis verosimiliter destruat: non sine ratione suspicari licebit, terram, unde animalium partibus similia corpora eruuntur, corpora illa hodie non producere. /Thus, since no bodies seem to be produced anew in harder soil, and since in many regions softer soil probably [as translated by Alex J. Pollock (1969)] destroys these bodies, we may suspect not without reason, that soil from which bodies resembling parts of animals are dug does not produce these bodies today' ([1], p. 720).

The words emphasized are from the same stem, *verisimilar/verisimilitude*, as in English being key words in the analysis of the hypothetico-deductive system axiomatized by Karl R. Popper in *Conjectures and Refutations* from analysis of studies by authors in Antiquity and Early Modern science, not the least in works by Galileo ([33], pp. 100,.).

In the *Canis* manuscript *evidenter* is crossed out and replaced by *verosimiliter* in Steno's hand (Fig. 6). *Verosimiliter* is found only this single time in Steno's printed works. In his CHAOS-Manuscript ([4], pp. 404, 419, 423, 440), *verisimile* is found four times in a long excerpt from Pierre Gassendi's *Animadversiones in Decimvm Librvm Diogenis Laertii, qvi est de Vita, Moribus, Placitisque Epicvri*, ..., published in Lyon in 1649. Could it be that Steno came over the word again in Galileo's text as quoted above during proof-reading the *Canis*?

3. *PRODROMUS*

Published two years after the *Specimen of Elements of Myology*, the *Prodromus de solido intra Solidum* contained another time-related model of transformation of solids visualizing

> *how six distinct aspects of Tuscany may be inferred from its present appearance, at the same time serve to make more intelligible those things that we have stated about the strata of the earth.* ([1], p. 822-825)

Steno's well-known illustration of the geological history of Tuscany in six schematic cross sections of landscapes was later used by Steno's student Holger Jacobæus when, as a professor at Copenhagen University, he fulfilled Steno's wish "to make more intelligible" such transformations (Fig. 7). Jacobæus' sketch and notes for geological lectures were published by Axel Garboe (1948)

[34]. They are among the few recordings of Steno's geology in his homeland, Denmark before the 19th century.

In the *Prodromus* a chapter on the growth of crystals by accretion of solid material to the surface is another description of a time-related solid transformation:

> *A crystal grows while new crystalline material is added to the exterior planes of the already formed crystal, so that there is no room at all here for the opinion of those who assert that crystals grow vegetatively.*
> *The external fluid receives crystalline material from the substance of the harder stratum, so that rocks of different types, emitting different fluids, produce crystals of different colours* ([1], pp. 794-796).

A lengthy digression concerns the division of the water space in the living organism in outer compartments, this means the space with direct connection to the surface of the body, and an inner compartment, subdivided into a common division for the whole body and inner divisions specific to each part (organs, muscles etc.) ([1], p. 779-78). Steno makes a practical, clinical point: "Most of the worms and stones inside our body are produced in the external fluid". He may even have developed an interest in studying crystal growth as a physician who sought to know how gallstones and bladder stones grow in what he called the external fluid.

After hurriedly completing the *Prodromus,* Steno traveled through Europe which included a visit to Innsbruck where he was asked by Anna de' Medici, the Archduchess of Austria and sister to Ferdinand II, to make an anatomical examination in a calf born with gross skull and brain malformations from hydrocephalus. Nonetheless as said, the animal had been able to sense. He concluded that hydrocephalus was caused by water held back by a cyst located 'at the root of the nostrils' near what is now called the optic chiasm. The cyst obstructed the passage of liquid between the brain's inner cavities. Such a 'foramen' was described in 1783 and named after the Scottish surgeon investigator, Alexander Monro. Among several conclusions Steno assumed that the malformation was hardly caused as commonly

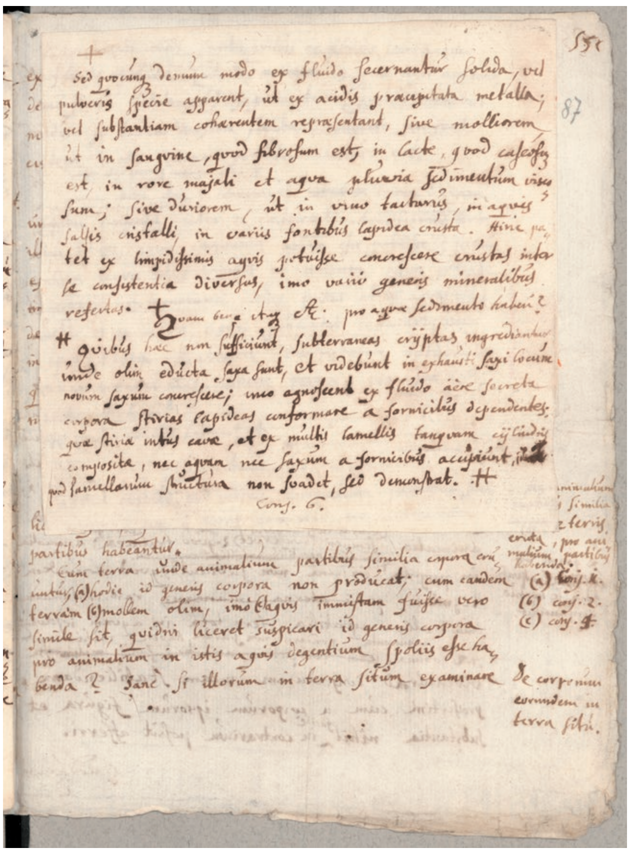


Figure 6. Page 81 from the *Canis* manuscript, part of *Elementorum Myologiae Specimen*, Royal National Library, Copenhagen, open access from www.kb.dk. Corrections and added subheadings in the margin are in Steno's handwriting (see also Fig. 5).

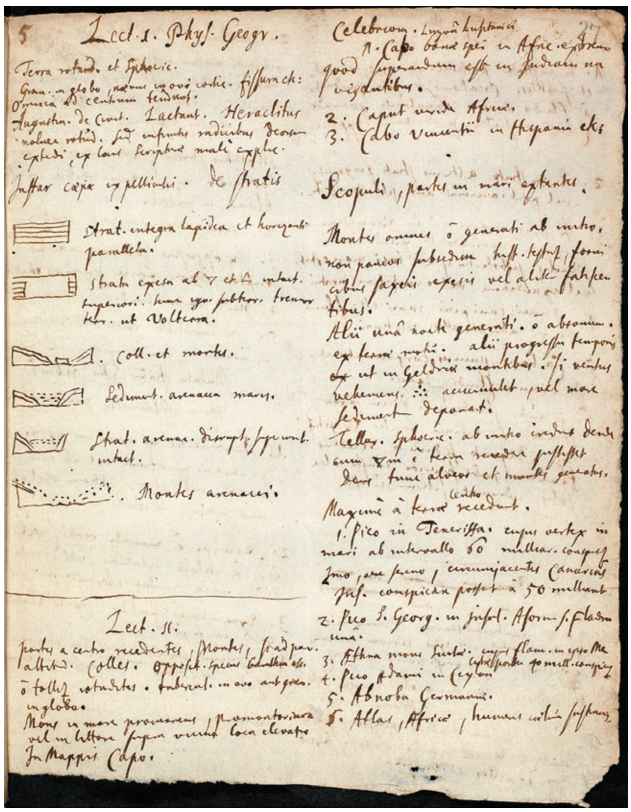


Figure 7. Steno's model of Tuscany drawn by his disciple Holger Jacobæus (1650-1701), professor at the University of Copenhagen since 1674, from his Lecture 1(Royal Danish Library, Manuscript collection, Thott 1108 4°) [34].

thought by visual imaginations in the mother - a cow. From details, the obstructing tumour may have been a *craniopharyngioma* as has been described in cattle and in humans [35].

When back in Copenhagen for two years, Steno gave an opening lecture, the *Proemium* … on January 28, 1673, in the re-opened Anatomical Theatre in Copenhagen. It was ostentatiously announced by his former teacher, professor Thomas Bartholin:

> *By the clemency of our very majestic King and Lord CHRISTIAN V, Father of the Fatherland, was called back to his homeland the most celebrated gentleman NIELS STENSEN, the new Democritus of the century. He consoles the hope of scholars, he will witness to the Fatherland that the fame obtained in the learned world by famous inventions and writings which respire bitten off nails, is not his private but public possession. In that intention, he started without envy, when scarcely he recently had set his foot in his native town, for the benefit of Asclepius' youngsters with lucky and ready hand to search the viscera of animals, in order to make visible every thing that was hidden. During the autumn of last year, though the weather was not enough favourable, he had publicly and privately dissected a human corps, two bears, a reindeer, a goat, hares, a cat, mice, a hedgehog, a squirrel, a dormouse, a monkey and other animals. Observations thereof I have put in the* Acta Medica et Philosophica *which are being printed. Not without exercise should pass the first months of the new year during these holidays, therefore he decided out of love for science and young people of the country, with the approval of the authorities and the agreement of the patron of the Academy Sir PETER REEDZ, Knight and the King's Great Counsellor to make in a humane corpse of female sex the experiment of his ability and doctrine in the Anatomical Theatre to the glory of God, the proficiency of Nature and the profit of the medical world.* ([1], pp. 849-852)

More on body liquids was expressed on February 2, 1673 during the subsequent public dissections over a week as, so to say, 'stenographed' by Holger Jacobæus, his student:

> (*It*) *is explained by the example of the building up of tartar on the teeth. There, indeed, the saliva clinging to the teeth gradually loses its more fluid parts, while thicker parts condense with time and harden. Or, to put forward a more common example, salt condenses in proportion to the evaporation of water from salt water* […] *both in the gallbladder, in the kidneys, in the small glands either of the tongue or of the rest of the body, and in the skin of gouty people, small stones condense in proportion to the evaporation of a thinner fluid* ([1], pp. 865-866)

Just two months later Steno writes about his situation in Copenhagen to his friend, the mathematician Vincenzo Viviani, in Florence. The newly recovered autograph letter is dated 18 April 1673 (Fig. 8):

> *The reason of delaying writing to you* […] *was the hope of hearing perhaps tomorrow the outcome regarding my position, that even now is still in doubt.* […] *If I live to the Holy year* [1675], *I hope to go to ask permission to come to the service of the Lord Prince* [Ferdinando], *as His Serene Majesty* [Cosimo III] *has very kindly told me that he would like me to serve him.*[8]

What an agony: few months after the *Proemium* lecture left in doubt of his situation with a wish to return to Florence. Steno continued giving dissections in small groups assisted by Holger Jacobaeus until he received royal permission to leave Copenhagen with a passport signed by Count Griffenfeld. After few months preparation in Florence he became a priest. Three years later he was called as Bishop in Northern Germany where he died in 1686.

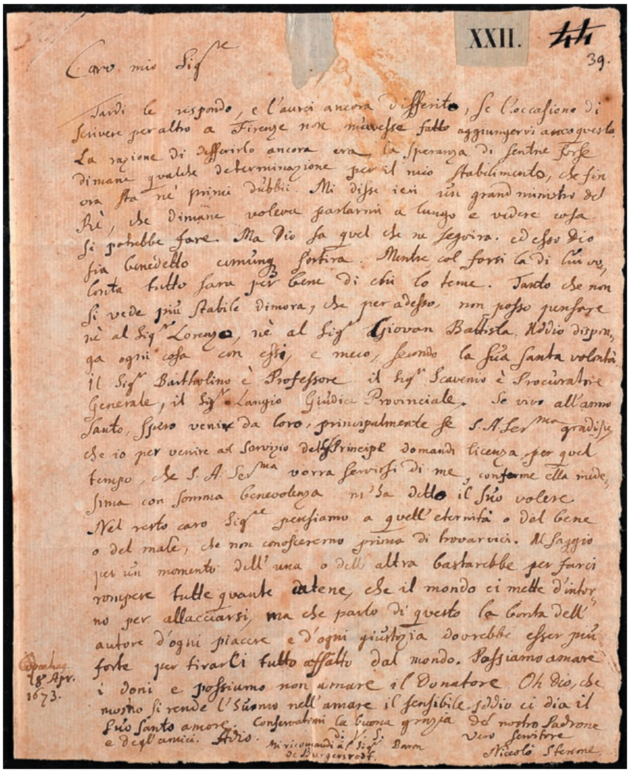
5. THE GALILEAN INSPIRATION

Steno, possibly inspired by his teacher Ole Borch, wrote on solvents and solutes in the *Chaos* Manuscript in 1659:

> *Beer from well water contains many impurities which overload the vessels of the mesentery etc., for in a barrel of rainwater a handful and more of dissolved earth is found. Hop has also its kinds of sediment. For if you distil beer, on the bottom you will find something like a sticky syrup* ([4], pp. 321-322).

On the same theme he gave the following brief remark without any implications:

[8] '… Mi disse ieri un grand ministro del Re, che dimane voleva parlarmi a lungo e vedere cosa si potre*bbe fare. Ma Dio sa quel che ne seguirà. Ed esso Dio sia benedetto comunque sortirà. Mentre, col farsi la di lui volontà* tutto sarà per bene di chi lo teme. Tanto che non si vede più stabile dimora, che per adesso, non posso pensare né al Sig. re Lorenzo, né al Sig. re Giovan Battista. Iddio disponga ogni cosa con essi, e meco, secondo la sua Santa volontà. Il Sig. re Bartholino è Professore il Sig. re Scavenio è Procuratore Generale, il Sig. re Langio Giudice Provinciale. Se vivo all'anno Santo, spero venir da loro, principalmente de se S. A. Ser. ma gradisse che io per venire ad servizio del Sig. re Principe domandi licenza per quel tempo, che S. A. Ser. ma vorrà servirsi di me, conforme ella midesima con somma benevolenza m'ha detto il suo volere …'. Royal Danish Library, Manuscript Collection, Shelf Mark: Acc. 2019/11. The letter was offered for sale on google by sophiararebooks.com in 2018 and was found in a search for the review in *Journal des Sçavants* of the 3rd edition of Steno's *Elementorum Myologiae Specimen,* 1711. The letter was donated to the Royal National Library in Copenhagen 2019.


XXII. 39.

Caro mio Sig.re

Tardi le rispondo, e l'haurei ancora differito, se l'occasione di
scrivere per altro a Firenze non m'havesse fatto aggiungervi ancora questa.
La ragione di differirlo ancora era la speranza di sentire forse
dimane qualche determinazione per il mio stabilimento, che fin
ora sta ne' primi dubbii. Mi disse ieri un grand ministro del
Rè, che dimane voleva parlarmi a lungo e vedere cosa
si potrebbe fare. Ma Dio sa quel che ne seguira. ed esso Dio
sia benedetto comunque sortira. Mentre col forti la di lui
bonta tutto sara per bene di chi lo teme. Tanto che non
si vede più stabile dimora, che per adesso, non posso pensare
nè al Sig.r Lorenzo, nè al Sig.r Giovan Battista. Iddio dispon-
ga ogni cosa con essi, e meco, secondo la sua santa volontà.
il Sig.r Bartholino è Professore il Sig.r Scavenio è Procuratore
Generale, il Sig.r Langio Giudice Provinciale. Se vivo all'anno
santo, spero venir da loro, principalmente se S.A.Ser.ma gradisse
che io per venire al servizio del Principe domandi licenza per quel
tempo, che S.A.Ser.ma vorra servirsi di me, conforme ella medes-
sima con somma benevolenza m'ha detto il suo volere.
Nel resto caro Sig.re pensiamo a quell'eternità o del bene
o del male, che non conosceremo prima di trovarvici. Il saggio
per un momento dell'una o dell'altra basterebbe per farci
rompere tutte quante catene, che il mondo ci mette d'intor-
no per allacciarsi, ma che parlo di questo la bonta dell'
autore d'ogni piacere e d'ogni giustizia dovrebbe esser più
forte per tirarci tutto affatto dal mondo. Possiamo amare
i doni e possiamo non amare il Donatore. Oh Dio, che
mostro si rende l'huomo nell'amare il sensibile. Iddio ci dia il
suo santo amore. Conservatemi la buona grazia del nostro Padrone
e degl'amici. Addio. Mi ricomandi al Sig.r Baron di V.S.
de Burgersrodt. Vero servitore
Nicolò Stenone

Copenhag.
18 Apr.
1673.

Figure 8. Steno's letter to Vincenzo Viviani, Shelf Mark: Acc. 2019/11 Royal Danish Library, the Manuscript Collection.

All sand has been water and can be changed into water. (4, p. 391)

As mentioned in the beginning Steno wrote an excerpt from Galileo's *Sidereus Nuncius*, ([4], p. 301-302) and eleven years later payed tribute to the late master when in the *Prodromus* he referred to "Magni Galilei" on liquid matters:

We are taught, moreover, by the most substantial proofs of the great Galileo *that heavier bodies of this kind can remain on the top surface of a fluid while one of their surfaces is in immediate contact with an overlying and lighter fluid of another sort; the aqueous nature of one of the fluids referred to is shown by the material of the strata that is deposited from the said fluid* ([1], p. 802/note 105).

Read in context, Steno's compliment was not as usually held just a tribute; nor is it a declaration of solidarity. Rather he demonstrates a cognition of shared interest with the late Galileo on the rules for the interaction of solids and liquids in contact as described by Galileo in the *Discourse on Bodies in Water - Discorso intorno alle cose, che stanno in su l'acqua e che in quella si muovono* (1612):

In water, there descend, even those particles that muddy it, whose smallness is such that they are not seen except in many hundreds together' ([5], p. 170).

Galileo concludes:

Nothing more need be said on this that has been said already; namely, that it is not [as held by Aristotle] *resistance to simple division, which does not exist in water or air, but heaviness of the medium that must be compared with the heaviness of the moveable. That being greater in the medium, the moveable will not descend in it, nor even submerge entirely, since in the place it occupies in the water there cannot rest a body weighing less than as much water; but if the moveable shall be heavier, it will descend to the bottom, to occupy place where it is more suitable to nature for it to rest than some less heavy body. And that is the single, true, proper and absolute cause of swimming above or going to the bottom, so that no other* [cause] plays a part in it ([35], p. 193)

Steno refers to Galileo's principles on solutes and solids in contact, and he must have known them when he described the transformation of originally horizontal sediments at the sea-bed as well as the growth of crystals by layering to the surface.

Steno should be remembered not just for the structures he described but for the descriptions of what happens to them, concepts that changed anatomy, physiology and geology into teaching of dynamic processes, *and* as a housekeeper of science ([13, 36])[9]. He did not attribute effects to imaginary effectors in the living organism like *animal spirits,* or a formative ability, *vis formans,* of rocks. Steno remained courteous when meeting in Rome P. Athanasius Kircher who excessed on such in his newly published work, *Mundus subterraneus,* with tales on bones of dragons, possibly, as has been suggested**,** fossils of extinct species.[10]

Steno was self-critical and respectful in his critique of the ancients. He emphasized that his knowledge, like theirs, would be revised. But Steno readily downed unfounded conceptions by Descartes on brain and muscles and by contemporary writers, and even one of his

[9] 'Mr. Willis gives us a quite peculiar system. He accommodates common sense in the corpus striatum, imagination in the corpus callosum and memory in the cortex or in the greyish substance which envelopes the white one. … How can he be so assured to make us believe that these operations occur in the bodies which he destines to them?' ([1], p. 608). See examples on Steno's scrutinty in cleaning up in brain research [37]. See also, Wilson (1961) on Steno's encounter with Croone at Montpellier 1666 [14].

[10] Steno remained courteous when meeting in Rome P. Athanasius Kircher who excessed on such effectors in his newly published work, *Mundus subterraneus*, with tales on bones and dragons, possibly, as has been suggested, fossil remains of extinct species: web address: http://christianlatin.blogspot.com/2008/08/athanasius-kirchers-natural-history-of.html

mentor Thomas Bartholin's favorite developments: since the nutritive chyle, the lymphatic drainage from the intestines, bypasses the liver as described by Pecquet, that organ had been "dethroned" from blood production; then Bartholin entrusted the heart with the task, on which, as quoted earlier, Steno bluntly stated, 'the heart is actually a muscle'.

Steno in research drew on inspiration from Galileo. He distinguished between what is not known as an entity and the little we know or can see, as expressed in his well-known saying:

> *Beautiful is what we see, more beautiful what we know, but by far the most beautiful is what we do not know* ([1], p. 857).

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[26] M. Brasier, *Philos. Trans. A Math. Phys. Eng. Sci.*, **2015**. https://doi.org/10.1098/rsta.2014.0254

[27] T. Yamada, in "The Revolution in Geology from the Renaissance to the Enlightenment" (Ed.: G. D. Rosenberg), *Geol. Soc. Am. Memoirs*, **2009**, 203, pp. 107-126. https://doi.org/10.1130/978-0-8137-1203-1-203.0.107

[28] A. Cutler, *The seashell on the mountaintop*, Dutton, New York, **2003.**

[29] T. Kardel, (Ed.: G. D. Rosenberg), *Geol. Soc. Am. Mem*., 2009, 203, pp. 127-134. https://doi.org/10.1130/978-0-8137-1203-1-203.0.127

[30] S.J. Gould, The titular Bishop of Titiopolis, *Nat. Hist.,* **1981**, 90, pp. 20-24.

[31] J.M. Hansen, in "The Revolution in Geology from the Renaissance to the Enlightenment" (Ed.: G. D. Rosenberg), *Geol. Soc. Am. Mem*., **2009**, 203, pp. 159-178.

[32] R. Andrault, *Early Sci. Med*., **2010**, 15, pp. 505–536. https://www.jstor.org/stable/20787426

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A Man with a Master Plan: Steno's Observations on Earth's History

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Abstract. We present specific sources, including specimens of the Medicean cabinet and geological outcrops in Tuscany, probably used by Nicolaus Steno to build a theory on the origin of organic fossils, crystals and sedimentary strata, in order to construct the history of the Earth based on universal geometric principles. Phenomena he observed in Tuscany and in preceding travels were revealing a sequence of events consistent with the biblical account. We propose that he devised his method to reconstruct a chronology of primordial events to demonstrate the historicity of the biblical creation in contrast to unorthodox thinking. This had been spreading in philosophical circles of northern Europe since the 1650s, circles frequented by Steno before his arrival in Tuscany in 1666. Steno knew in advance what places to visit to find fossils, from literature such as Michele Mercati's *Metallotheca*. This was a manuscript owned by the Florentine Carlo Dati, whom Steno probably heard about while in Paris in 1664-1665. In Tuscany he soon formed a tight interaction on matters regarding the interpretation of fossils with the local community of learned men. These included Giovanni Alfonso Borelli who was asked by Prince Leopoldo de' Medici to provide Steno with fossils from Sicily and Malta. Steno's theory and scale-independent, geometrical method of inquiry of geological objects found in Tuscany is hinted at in his *Canis Carchariae Dissectum Caput*, a geological essay completed in a few months in 1666. The theory was published in its most complete form in the so-called *Prodromus* of 1669. In both works he demonstrated that fossils in younger strata in the Tuscan hills, such as shark teeth and molluscan shells, have an origin analogous to solids which living animals form. In both essays he explicitly related the deposition of strata with marine fossils to the biblical flood, an idea foreshadowed in "Chaos," his oldest known manuscript of 1659, when he was a student in Copenhagen. He found no fossils in older sandstones of the Apennines and understood those strata to have formed before the creation of life. These discoveries and other observations he made in Tuscany were, for Steno, the final proof that natural philosophy and biblical revelation disclose in synergy the mysteries of God's creation.

Keywords: Nicolaus Steno, Meaning of Fossils, Natural Philosophy, Accademia del Cimento, Biblical Chronology, Early Modern Science.

1. INTRODUCTION

The most important and lasting contribution that Nicolaus Steno (1638-1686) left to modern science is the 78-page book titled *The Prodromus to a*

Dissertation on a Solid Naturally Contained Within a Solid (the *Prodromus* in short).[1] The dissertation that the title alluded to never followed, and the *Prodromus* was the last published scientific essay of the intense and brief career of a young researcher bound to influence his generation of natural philosophers.[2] Most of his precedent-setting works were centered on anatomical research and the study of the animal body, but the *Prodromus* dealt with crystals, fossils and rocks. Why turning to a different subject? And why Steno accepted the parallelism between the natural history revealed in the rock record and the biblical narrative? Since his scientific endeavour ended in coincidence with his conversion to Catholicism and the start of a vocation in theology, modern understanding has to deal with history of science and history of religion at the same time. Consequently the aim behind the *Prodromus* remains obscure unless readers are familiar with both contexts. According to biographers who emphasized Steno's role in the history of science, such as the late Gustav Scherz (1895-1971), the standard story is that Steno turned to the study of fossils in 1666 when he realized, while casually studying the anatomy of a shark's head, that fossils called *glossopetrae* (meaning "tongue stones") were actually shark's teeth and not, as generally supposed, sports of nature. A second widely-accepted narrative suggests that denying biblical chronology in the face of hard empirical evidence was "a losing game,"[3] so that Steno "continued to hesitate about the implications of his finding"[4] and in the final chapter of the *Prodromus* "took care to reassure readers that his science did not contradict the Bible."[5] This emphasis implies that during those years some empirical evidence, or science in the modern sense, could undermine the credibility of biblical chronology. Historians of religion know very well, however, that it was not natural philosophy, but textual criticism itself, which at that time called into question Scripture. Furthermore, criticism stemmed from disputatious freethinkers, such as the French Isaac La Peyrère (1596-1676) and Richard Simon (1638-1712), Isaac Vossius (1616-1689) and Baruch Spinoza (1632-1677) in the Dutch Republic, and Francis Lodwick (1616-1694) in England, people who had no public followers of their caliber until the second half of the eighteenth century.[6] Indeed, biblical chronology was understood to be a science with its worthy followers, and seventeenth-century natural philosophers did not doubt that the Book of Genesis was a reliable historical account of the distant past. This needed interpretation, the reason why a science of biblical chronology was necessary.[7] This means that the parallelism drawn by Steno in the last chapter of the *Prodromus* between an empirical reconstruction of historical events and the biblical account, from Creation to repopulation of the Earth after the Deluge, was not motived by fear of the authorities of the Church to which he had recently converted, as instead suggested by some.[8] Steno, like any other natural philosopher of his time, took the Bible as "obviously and predominantly *historical*," an account to be carefully interpreted using all available translations.[9] The evidence presented in the present paper reinforces the opinion that Steno sincerely wanted to prove that he had found a limited, but relevant and additional means to reconstruct history. Steno's latest scientific production is underlain by a search for true religion and a way to reconcile natural philosophy and biblical revelation, in years when unorthodox thinking triggered debate in northern Europe.[10] It is suggested that Steno actually had planned field work before moving from Paris to Tuscany.

The standard point of view is therefore disputed and it is hypothesised that the young Dane knew that in Italy he could find evidence for a reconstruction of primordial history based on an unprecedented way to study crystals, fossils and rocks. Since his student years, Steno's multifaceted general research plan to uncover the mysteries of God's Creation included aspects of his ongoing

[1] N. Stensen, *De Solido Intra Solidum Naturaliter Contento Dissertationis Prodromus,* Florence, Stella, **1669** (*Prodromus* in following notes). English translation, pp. 621-660, in T. Kardel, P. Maquet, *Nicolaus Steno, Biography and Original Papers of a 17th Century Scientist*, 1st edition, Heidelberg, Springer, **2013** (K&M in following notes).

[2] A treatise on precious stones, written after the *Prodromus*, was never published, indicating that Steno left the scientific community by 1669: F. Sobiech, in *The Revolution in Geology from the Renaissance to the Enlightenment* (Ed.: G. D. Rosenberg), *Geol. Soc. Am. Mem.*, **2009**, *203*, 179-186.

[3] A. Cutler, *The seashell on the mountaintop*. Dutton, New York, **2003**, pp. 5-16, 115-122, 191-192.

[4] P. Findlen, *Possessing Nature: museums, collecting and scientific culture in early modern Italy* University of California Press, Berkeley, **1994**, p. 237.

[5] R. Rappaport, *When geologists were historians*, Cornell University Press, Ithaca and London, **1997**, p. 201.

[6] R. Rappaport in ref. 5, p. 76. Criticism towards historicity of the biblical narrative was discussed only privately, and in small circles: see an eloquent example in W. Poole, *Scripture and Scolarship in Early Modern England* (Eds. A. Hessayon, N. Keene), Ashgate, Aldershot, Hampshire, **2006**, pp. 41-56

[7] M. J. S. Rudwick, *Earth's deep history*. Chicago University Press, Chicago, **2014**, pp. 9-30.

[8] A. Cutler in ref. 3, pp. 5-16, 192.

[9] Quote and emphasis from R. Rappaport in ref. 5, p. 72. On the role of the different translations of the Bible see E. Jorink, " "Horrible and blasphemous": Isaac La Peyrère, Isaac Vossius and the emergence of radical biblical criticism in the Dutch Republic," in *Nature and Scripture in the Abrahamic religions: up to 1700* (Eds. J. M. van der Meer, S. Mandelbrote), Brill, Leiden, **2016**, pp. 429-450.

[10] S. Miniati, *Nicholas Steno's challenge for truth. Reconciling science and faith*, Milan, Franco Angeli, **2009**, 336 p.

studies of anatomy, and other studies aimed at proving the historicity of the biblical account by geometrical means. His contemporaries understood the *Prodromus* as such, looking forward to seeing the full dissertation published.

It is questioned whether Steno's interest in the origin of fossils stemmed from a serendipitous discovery that glossopetrae were shark's teeth (a finding already publicly demonstrated in 1616 by Fabio Colonna).[11] Instead of moving top-down from philosophical, metaphysical and theological questions that mattered to Steno and his peers, this study reconsiders the timing with which he collected geological data in Tuscany, what textual sources on local paleontological sites he most certainly drew from, and his relationships with a network of sources. The amount of data he swiftly collected and the conclusions he drew in the very first months after his arrival in Florence imply that he had planned to do geological research, a plan that ultimately related to chronology of biblical events and had of course something to do with debates on the intepretation of Scripture occurring in cultural circles that he had frequented before 1666. Those circles embodied the spirit of the 'new philosophy', as termed by John Donne in 1611,[12] and at least in part coincided with 'the Republic of Letters', a transnational community that cultivated science based on observation, experiments and mathematics, not on scholastic authority.

His work in Tuscany, started at the age of 28, came at the climax of a series of readings and experiences traced back to 1659, when he was 21 years-old. These had made him receptive to evidence concerning the nature of fossils and sedimentary rocks and will be reviewed as such. Learned men at the Medici court were connected with European intellectual circles and would have offered Steno plenty of knowledge on geological matters. The Italian tradition dealing with *Re Metallica*, "metallic things", or geological data in the modern sense, with studies practiced by Italian Renaissance and early modern writers, such as Andrea Cesalpino (1524-1603), Michele Mercati (1541-1593), Ferrante Imperato (1550-1631) and Fabio Colonna (1567-1640) was famed enough to attract Steno to visit cabinets of natural history and rock outcrops from which geological specimens came. The geological data he referred to have remained somewhat obscure, because none of the essays he published in Italy, with few exceptions, contain clear information on location and description of specific places he visited and specimens he studied. This situation has influenced the perception of the *Prodromus* as an abstract work that assembled an "odd array of material,"[13] an opinion that the present paper will attempt to dispel.

2. A MAN WITH A PLAN

Steno's philosophical and religious background must be recalled in order to understand the reason he searched for confirmation of Scripture in Nature. Empiricism underlay both his natural philosophy and his theology[14] and transcended what is recognized today as a separation of physics from metaphysics. Within the physical world, Steno dealt jointly with 'geological', chemical and anatomical observations. This he did in the light of the Scripture since at least 1659, when he recorded in his journal, entitled "Chaos", lessons which he derived from the writing of others.[15] This collection of extracts, an aid for the memory when he was a student and a sort of commonplace book,[16] is Steno's oldest known manuscript. It starts with words and concepts directly referred to the Christian Faith and the writings of Moses, the purported author of the Book of Genesis:

In the name of Jesus
CHAOS
Not out of Aristotle's [elements]

[11] F. Columnus, *De Glossopetris Dissertatio*. In *Fabii Columnae Lyncei Purpura*, Rome, **1616**, pp. 31-39. See M. J. S. Rudwick, *The meaning of fossils. Episodes in the history of paleontology*, Chicago, University of Chicago Press, 2nd edition, 1976 [**1972**], pp. 42-44; A. Ottaviani, "La natura senza inventario: aspetti della ricerca naturalistica del linceo Fabio Colonna", *Physis*, **1997**, 34, pp. 31-70.

[12] "And new philosophy calls all in doubt,/The element of fire is quite put out,/The sun is lost, and th' earth, and no man's wit/Can well direct him where to look for it:" J. Donne, conclusion from *An Anatomy of the World*, cited in D. Wootton, *The invention of science: a new history of the scientific revolution*, New York, Harper Perennial, **2015**. Donne writes about a 'new philosophy' a year after the publication of Galileo Galilei's *Sidereus Nuncius*, and is thus identified by Wotton as the first accountable testimony to the birth of modern science.

[13] R. Rappaport in ref. 5, pp. 99-101; but see M. J. S. Rudwick, *The meaning of fossils. Episodes in the history of paleontology*, Chicago, University of Chicago Press, 2nd edition, 1976 [**1972**], pp. 58-60; D. Garber, *Steno and the Philosophers* (Eds.: R. Andrault, M. Lærke), Brill, Leiden, **2018**, (A&L in following notes), pp. 201-232.

[14] F. Sobiech, *Ethos, bioethics, and sexual ethics in work and reception of the anatomist Niels Stensen (1638-1686)*, Springer, **2016**, pp. 30-35.

[15] A. Ziggelaar in N. Stensen, *Acta Hist. Sci. Nat. Med.* (Ed.: A. Ziggelaar), 1997 [**1659**] (*Chaos* in following notes), *44*, 453 pp.; G. D. Rosenberg, *Geol.*, **2006**, *34*, pp. 793-796; S. Olden-Jørgensen, in ref. 2 (Rosenberg), pp. 149-157.

[16] The practice of writing commonplace books, a form of text collections, emerged particularly during the late Renaissance and remained in use among literate people during the early modern age: E. Havens, *Commonplace books: a history of manuscripts and printed books from antiquity to the twentieth century*. University Press of New England, **2002**, 99 pp.

That man is composed of the four elements is against Holy Scripture, where Moses only mentions water and earth. For Aristotle's air nowhere appears and fire is an accident. […] bodies are only resolved into water and earth.[17]

The first two lines can be regarded as a synthesis of the first part of the Creation seen form a Christian perspective: "in the beginning was the Word […] and the Word was God" (meaning Jesus), says the Prologue according to the evangelist John. In this sense, 'In the name of Jesus' right before 'CHAOS' becomes God's word commanding order to raise from non-order. This last concept is confirmed in a later remark in Steno's *Elementorum Myologiae Specimen* of 1667: "in Holy Scripture it is said that the world has come forth from 'unseen' matter as from chaos."[18] The other part of the opening regards the third day of the biblical Creation, when God separated dry land from water. Steno quoted the passage from the surgeon Cornelius Schylander's *Practica chirurgiae brevis et facilis* (1575),[19] where the authority of Aristotle on the number of elements is submitted to the authority of the Bible: the basic elements all bodies are made of are water and earth (air and fire being secondary). Furthermore, taking the point of view of a student writing not for publication, Steno's private collection of excerpts seems also to start with an auspice that his knowledge be ordered, from the chaotic form of the commonplace book into that of a mature anatomist.[20] Several times Steno, while excerpting the books he was reading, fell into despair and doubted his ability to bring order to the many subjects he approached.[21] He subtly declared an attempt to reach a unitary comprehension of nature and in the same page he confirmed that 'the profane is not to be excluded from the sacred' (a quote taken from Jeremias Drexel's *Ioseph Aegypti prorex descriptus* of 1641).[22]

Most of the above, written in 1659, are about medical matters, but water, earth and Scripture are for the first time related with fossils in some revealing quotes taken from Pierre Borel's *Historiarum et observationum Medico-Physicarum* (1656). In a passage Steno focused on analogies between the human body and the Earth that allowed him to realize that marine fossils were evidence of an "ancient deluge".

Singular stones of the bladder, shells turned into stones. Therefore stones in places that lie very far from the sea, it is certain that seas change their beds. In the right kidney a grey stone was observed, in the left kidney clay. […]
Snails, shells, oysters, fish etc. found petrified on places far remote from the sea. Either they have remained there after an ancient deluge or because the bed of the seas has slowly changed. On the change of the surface of the Earth I plan a book.[23]

The last sentence, although taken from Borel, may well allude also to Steno's program, at least denoting what he considered worthy of serious consideration when he was 21. The original Borel's text reports that:

Near the town of Montpellier I found large petrified oysters, mussels and even fossil fishes […] all these things show that in ancient times the flood for long covered this place (as discovered also elsewhere, very far from the sea), that is to say that the sea has changed position, (which I will prove in my book 'On the changed position of the globe'*, and at other places I saw dragon's teeth), so the sea receded from innumerable places.*[24]

The importance of quotes taken from this contemporary French cartesian philosopher is underlined by side notes made by Steno in the 1659 manuscript.[25] The above passage also indicates the region around Montpellier as one where marine fossils occur, suggesting why Steno sojourned in that town of southern France in winter 1665-1666, before continuing his trip to Tuscany.

As a young student, Steno approved the method of inquiry laid out by René Descartes in the *Discourse de le méthode* (1637) and *Les Principes de la philosophie* (1644), without sharing the cartesian preference to separate natural philosophy from theology.[26] In the words of historian of science Justin E.H. Smith, young Steno appears "speculative, somewhat mystically inclined,

[17] N. Stensen, *Chaos*, in ref. 15, p. 21.
[18] N. Stensen, *Elementorum Myologiae Specimen, seu Musculi Descriptio Geometrica*, in ref. 1 (K&M), p. 435; J. Smith, in ref. 13 (A&L), pp. 177-200.
[19] A. Ziggelaar, in ref. 15, p. 103.
[20] Francis Bacon praised the activity of text collecting in his *The advancement of learning*: "there scarcely can be a thing more useful, even to ancient, and popular sciences, than a solid, and good aid to memory; that is, a substantial and learned digest of common places. […] I hold that the diligence and pains in collecting commonplaces, is of great use and certainty in studying": quoted in E. Havens, *The Yale University Library Gazette*, 76, **2002**, pp. 136-153.
[21] F. Sobiech, in ref. 14, pp. 59-61.
[22] N. Stensen, *Chaos*, in ref. 15, p. 22; Smith, in ref. 2, p. 197.
[23] N. Stensen, *Chaos*, in ref. 15, pp. 46, 58-59. The original Borel's text relates the presence of marine fossils with the biblical flood, with writing a book on the argument.
[24] P. Borel, *Historiarum et observationum Medico-Physicarum*, Billaine, Paris, **1656**, p. 261. The italics are in the original text and refer to the title of the book that Borel had planned to write.
[25] A. Ziggelaar, in ref. 2 (Rosenberg), pp. 135-142. J. Bek-Thomson, ref. 2 (Rosenberg), p. 289.
[26] E. Jorink, *Reading the book of nature in the Dutch Golden Age, 1575–1715*, Brill, Leiden, **2010**, p. 16. See also Olden-Jørgensen in ref. 2 (Rosenberg), pp. 149-157. On the role of Borch in directing Steno's education, see A. Ziggelaar, in ref. 2 (Rosenberg), pp. 135-142.

and at the same time keen on absorbing the latest lessons from empirical natural philosophy, including those of Bacon, Descartes, and others, even when these come from thinkers who do not share the same mystical and theological concerns."[27] When in 1661 he went to study medicine in the Low Countries, he connected with the circle of Dutch *savants* and *curieux*, first in the hotbed of radical thinkers that was Amsterdam, then in nearby Leiden. There he had relations "far from marginal" with the unorthodox philosopher Baruch Spinoza[28] and the innovative physician Johannes Swammerdam.[29] Swammerdam and Steno were fellow students and close friends in Leiden from 1661-1663 and then in Paris in 1664, the two sharing a motivation to search for a bridge between natural philosophy and true religion. Swammerdam maintained that skilful dissections of animals, even insects, disclosed to the anatomist the immense wisdom that God had instilled in the minutest parts of creation. The two came to believe that 'studying the intricate fabric of anatomical structures was a tribute to God, the omniscient architect'.[30] They lived in a critical place at the critical time for the future of religion when, following the interventions of Descartes and Spinoza, 'the relation between belief and natural science became problematic'.[31] The philosophy underlying Steno's and Swammerdam's research consciously moved away from the *Deus sive natura* principle of Spinoza, a motto that denoted the identity between the infinite substance of God and the finiteness of Nature. The two chose instead a religion grounded on 'the argument from design', the idea that God is not identical to nature, but is the great Architect, whose brilliance can be deduced from the 'great fabric of the world'.[32]

Historiographers still discuss if, in his early twenties, Steno was a genuine Lutheran[33] or a deist, however "*sui generis*",[34] yet opinions converge in depicting those years as a period during which he gradually lost faith in cartesian dogmatism and a mechanistic perspective, instead becoming more meditative and inquisitive in religious matters. In autumn 1664 he joined Swammerdam in Paris, where, for nearly a year, both were hosted by Melchisédec Thévenot (1620-1692). Thévenot had been a diplomat in Italy during the 1650s, and was an experimentalist in close contact with the Accademia del Cimento in Florence, himself hosting a sort of academy in his house. There Steno met with Pierre Borel and admired his skills, as he recalled two years later:

> *In Paris, in the Academy at the house of my great friend Thévenot, I have seen Borel, greatly skilled in chemistry, pour together two quite clear liquids which immediately became so solid that not even a drop left the glass container when it was inverted.*[35]

Thévenot was also a collector of travel accounts from long-distance voyagers and the owner of a cabinet of curiosities.[36] Among Thévenot's other connections was Athanasius Kircher, founder in 1651 of 'Museum Kircherianum' in Rome. In the early 1660s Kircher's popularity was immense, based on his encyclopaedic interests, vast experience, and even vaster imagination regarding late Renaissance visions in natural matters that often conflicted with the new philosophy. Savants throughout Europe, including Prince Leopold of Medici[37] in Florence, had been awaiting the publication of his *Mundus subterraneus* in 1664,[38] preceded in 1641 by *Magnes sive de arte magnetica*, extensively quoted in Steno's *Chaos*.

One of Kircher's disciples on sinology at the Roman College was the Jesuit missionary Martino Martini, author in 1658 of 'History of China',[39] a book that pro-

[27] J. E. H. Smith, in ref. 13 (A&L), pp. 177-200.

[28] Quote from P. Totaro, "Ho certi amici in Ollandi", *Analecta Romana Instituti Danici*, **2002**, suppl. 31, pp. 27–38. On the relation between Steno and Spinoza, see also G. Scherz, in ref. 1 (K&M), pp. 91-92, and particularly S. Miniati, *Scienza, filosofia e religione nell'opera di Niels Stensen* (Eds. M. A. Vitoria, F. J. Insa Gómez), Pagnini, Firenze, **2020**, pp.

[29] E. Jorink, in ref. 13 (A&L), p. 16.

[30] E. Jorink, quoted in ref. 13 (A&L), p. 29.

[31] E. Jorink, quoted in ref. 13 (A&L), p. 16.

[32] E. Jorink, quoted in ref. 13 (A&L), p. 18.

[33] S. Miniati, ref. 10.

[34] S. Olden-Jørgensen, in ref. 2 (Rosenberg), pp. 149-157; F. Sobiech, ref. 14.

[35] N. Stensen, *Canis Carchariae Dissectum Caput,* Florence, Stella, **1667** (*Canis Carchariae* in following notes). English translation in ref. 1 (K&M), p. 591.

[36] N. Dew, in *Bringing the World to Early Modern Europe: Travel Accounts and Their Audience* (Ed.: Mancall), Brill, Leiden, **2007**, p. 49. The correspondence between Thévenot and future members of the Cimento Academy dated back to 1643, continued through the years and included letters to Prince Leopold of Medici, in Florence, on experimental matters (1660-1666): ref. 38 (MG); W. E. K. Middleton, *The Experimenters: a study of the Accademia del Cimento*, John Hopkins Press, Baltimore, **1971**, 415 pp.

[37] Prince Leopold of Medici (1617-1675) promoted the publication of Galileo Galilei works (1655-1666) and the activities of the Accademia del Cimento (1657-1667): Knowles Middleton, ref. 36; A. Mirto, *Dizionario Biografico degli Italiani*, **2009**, 73, pp. 106-12. As an erudite collector of art and antiquities, in 1662-1668 he had established a productive European network: S. Dall'Aglio, *J. Hist. Collect.* 12/12/**2019**, pp. 1-12.

[38] W. C. Parcell, in ref. 2 (Rosenberg), p. 64-66; letter by A. Kircher (15 august 1965) to Prince Leopold, in digital archive, Museo Galileo (MG in following notes), Gal. 277, f. 215r: https://www.museogalileo.it/it/biblioteca-e-istituto-di-ricerca/biblioteca-e-archivi/archivio-storico.html (accessed on 24 May 2020).

[39] 'Historia' of the title retains its traditional significance of 'collection of facts', not its reductive modern use as 'chronology of events'. This is evident from Martini's address to the reader, 'Extrema Asia sive Sinarum Imperii compendio & annorum ordine comprehensam Historiam': M. Martini, *Sinicae Historiae*, Blaeu, Amsterdam, **1659**, p. 6. For the use of 'Historia' in Steno and his contemporaries, see J. Bek-Thomsen, in ref.

posed a chronology different from the biblical.[40] It is reasonable to suppose that Steno discussed Earth's history at Thévenot's circle in 1664-1665, in the wake of debates in Amsterdam circles of freethinkers, where the idea that human history is older than history told in the Old Testament had found sustainers[41] and the universality of the noachian flood was questioned.[42] A new type of anatomical observation, this time on a grand scale, so as to see the body of the Earth cut open, would have pushed him to move south where he knew he could observe fossils on the field.[43] Thévenot formed a bridge with the liberal court of Ferdinand II, Grand Duke of Tuscany, and his brother, Prince Leopold. At the Medici court another international circle had gathered, including the French oriental philologist Barthélemy d'Herbelot (1625-1695). By moving to Florence Steno could hope to earn a wage to pursue his research, whether on muscles or on fossils and their context.[44] The Florentine Carlo Dati (1619-1696), one of the members of the Accademia del Cimento and a correspondent with learned men from Paris,[45] was also a correspondent of Thévenot's. Steno had probably heard in advance about the paleontological heritage of Tuscany, well known to Carlo Dati as it will be shown. From Tuscany he could move further south, until eventually reaching Sicily and Malta and there collect other fossils.

First in the Dutch Republic, then in Paris, Steno was thus in the middle of a fierce polemic on which he could hardly remain neutral, judging from his inquisitivity on religious matters.

2 (Rosenberg), pp. 296-297; N. Morello, *Niccolò Stenone e la scienza in Toscana alla fine del '600* (Eds.: L. Negri, N. Morello, P. Galluzzi), Laurenziana, Firenze, **1986**, pp. 67-89.

[40] Martino Martini (1614-1661) dominated European knowledge of China in the period 1654-87: N. Dew, *Orientalism in Louis XIV's France*, Oxford University Press, Oxford, **2009**, 302 p.; E. Jorink, D. Miert, *Isaac Vossius (1618-1689) between science and scholarship*, Brill, Leiden, **2012**, 352 p.; see also R. Rappaport, ref. 5.

[41] Martini's book influenced the reception of the preadamite theory by Isaac La Peyrère (1596-1676), particularly in the Dutch Republic starting from the late 1650s: R. H. Popkin, *Isaac La Peyrère (1596-1676): his life, work, and influence*, Brill, Leiden, **1987**, pp. 85-87; J. L. Morrow, *Three skeptics and the Bible: La Peyrère, Hobbes, Spinoza, and their Reception*, Eugene, Pickwick, **2016**, pp. 83-84; A. Grafton, "Isaac Vossius, Chronologer", in ref. 40 (E. Jorink, D. Miert), pp. 43-84.

[42] A. Ottaviani, *Giorn. Crit. Filosof. It.*, **2017**, *13*, 272-301.

[43] J. Bek-Thomsen, in ref. 2 (Rosenberg).

[44] N. Dew, ref. 40, pp. 62-76. 'For many years, a prominent position inside the Medici Court meant an attractive lifestyle and high wages': L. Boschiero, *Experiment and natural philosophy in seventeenth-century Tuscany. The history of the Accademia del Cimento*, Springer, Dordrecht, **2007**, p. 20.

[45] Carlo Roberto Dati, humanist, disciple of Galileo and experimentalist, in close contact with Jean-Baptiste Colbert, Minister of the Finances under Louis XIV, was consulted in 1666 for the birth of the *Académie de Sciences*. See N. Dew, ref. 40, p. 53, and W. E. K. Middleton, ref. 36.

3. THE NATURE OF TUSCANY

Steno arrived in Tuscany in April 1666. Ferdinand II and Prince Leopold recognized him as an outstanding natural philospher, an anatomist whose public dissection of a human brain performed in Paris in October, 1665[46] proved Descartes wrong about the manner in which this organ functions.[47] By December of the same year, Steno had completed the essay *Canis Carchariae Dissectum Caput* which ended with a "digression on bodies resembling parts of animals that are dug from the earth", a writing where 'tongue stones" were interpreted as sharks' teeth.[48] This essay was subsequently published in April 1667 as an appendix to his treatise on myology.[49] The interpretation of the dissection as the starting point of a research on fossils is probably based on Steno's brief account of his scientific career, written in the opening pages of the *Prodromus* ("To take me away from a detailed account of the muscles, a shark of prodigious size was thrown up by your seas"),[50] a rhetorical artifice to emphasize that in his life he had been accustomed to submit to someone else's will. Instead, he could hardly collect all evidences contained in the 'digression' between October[51] and December, so he had carried out the many observations on fossils and the sedimentary strata in which they were found before the dissection. As for the reason to carry out any field activity, *Canis Carchariae* already shows that his interest for marine fossils was related to two events narrated in the Scripture, two cornerstones of Earth's history presented in the *Prodromus*. The first event was the separation of solid matter from fluid, on the third day of Creation ("And God said, 'Let the waters under the sky be gathered together into one place, and let the dry land appear'": Gen 1, 9), an interest foreshadowed by the opening quote of the *Chaos* manuscript (see above note 17). The second event was the Universal Deluge ("The flood continued forty days on the earth; and the waters increased, […] and it rose high above the earth": Gen 7, 17), referred to in Borel's quote transcribed in 1659 (see above notes 23-24). Both events relate to a universal fluid covering all or most of the globe.

Canis Carchariae reports that different types of fossils were contained in two types of strata, one hardened the other soft, separated by surfaces that deviated from

[46] N. Stensen, *Discours sur l'anatomie du cerveau*, Paris, Ninville, 1669. English translation in K&M, pp. 507-527; R. Andrault in ref. 13 (A&L), pp. 87-112.

[47] A. Cutler in ref. 3, p. 53.

[48] N. Stensen, *Canis Carchariae*, in ref. 1 (K&M), pp. 571-595.

[49] N. Stensen, *Myologiae Specimen*, in ref. 1 (K&M), pp. 545-570.

[50] N. Stensen, *Canis Carchariae*, in ref. 1 (K&M), pp. 623-624.

[51] A. Cutler in ref. 3, p. 53.

horizontality (a geometric character that implies tilting of strata after their deposition and that would become a central argument of the *Prodromus*):

> *The soil from which bodies resembling parts of aquatic animals are dug is in certain places rather hard, like tufa and other kinds of stone; in other places it is rather soft like clay or sand* […]. *In various places, I have seen that the said soil is composed of layers superimposed on each other at an angle to the horizon.* […] *In those soils that I have been able to observe up to now, bodies of different kinds have been concealed in the same soil, sometimes in the harder, and sometimes the softer sort. I have observed that the number of these bodies in clay is quite large in the surface but quite small in the soil itself* .[52]
> *Very many oyster shells are found in some regions, deformed and hardened into one lump; sometimes also, broken scallops and mussels are dug up; some people have seen, in the same place, many tongue stones clinging as it were to the same matrix.*[53]

Based on the comparison of 'tongue stones' with the teeth of the large shark he had dissected, he hypothesised in the essay that they did not grow in the earth, an opinion still held by many.[54] Steno had surely seen 'tongue stones' in Copenhagen in the museum of Ole Worm (1588-1654),[55] and learned about them through his teacher Thomas Bartholin (1616-1680), who had written a book on glossopetrae after travelling to Malta in 1644.[56] But he had never seen them in earlier travels:

> *I do not yet have the knowledge of this matter* [the tongue stones] *to pass judgment on it here; and though my travels have taken me through various places of this kind, nevertheless, I do not dare to guarantee that what I shall observe in the rest of my journey will be similar to what I have observed up to now. Chiefly, since I have not yet seen what my very famous teacher Bartholin observed in his journey to Malta.*[57]

'Several places of this kind' refers to localities of outcrops where assemblages of marine animal fossils are embedded in compact or hardened rock. Following Borel's indication, he had possibly seen strata with marine shells around Montpellier, where he had met with other savants interested in the study of fossils, such as John Ray (1627-1705) and Martin Lister (1638-1717).[58] Above all, he must have been informed that Tuscany was particularly suited to carry out that type of fieldwork. Although 'tongue stones' were difficult to find, fossils they were usually associated with were a useful substitute (see comment '*some people have seen, in the same place* [of oysters, scallops and mussels], *many tongue stones*' above).[59] The most important influence was an unpublished 'field guide' by the Tuscan Michele Mercati, a manuscript handed to him in Florence.[60] In the preceding century, Mercati had systematically arranged the Pope's collection of minerals, stones and fossils in 19 large and expensive cabinets to form the Vatican museum called *Metallotheca*. The manuscript was owned by Carlo Dati, who had lent Steno two of the engravings made for the *Metallotheca* which the Dane used to illustrate the *Canis Carchariae* essay,[61] as well as the manuscript itself. This told about 'instructions' that interested Steno, as he himself revealed:

> *Mercati's manuscript* [contains] *much that is well worth knowing and a wealth of varied instruction about soils, salts, oily fluids, stones, bodies of idiomorphic shapes, and so on; this manuscript would have remained buried in eternal darkness, had not the very learned Dati's skill brought it out of the underworld and provided an opportunity for it to be exposed to the light of day.*[62]

Mercati revealed that at his hometown of San Miniato (locality 3 in Fig. 1), a place famous for marine shell beds as recorded also by Leonardo da Vinci (1453-1519),[63] large tongue stones were found with oysters (Fig. 2). Mercati had subdivided tongue stones on the basis of size and shape and pictured them in three beautiful

[52] N. Stensen, *Canis Carchariae*, in ref. 1 (K&M), p. 585.
[53] N. Stensen, *Canis Carchariae*, in ref. 1 (K&M), p. 586.
[54] N. Morello, ref. 39.
[55] For the *Museum Wurmianum* in Copenhagen and its role for Steno's upbringing, see Rosenberg, ref. 15 and appendix; for the significance of private museum collections for seventeenth century natural philosophers see Rappaport, ref. 5, pp. 53-55.
[56] Bartholin's essay on glossopetrae is now lost. Scherz, in ref. 1 (K&M), p. 38; A. Ziggelaar in ref. 15, pp. 466-469; I. H. Porter, *Med. hist.*, 7, **1963**, pp. 99-125; A. Ottaviani, *Schede Umanistiche, Riv. sem. Arch. Um. Rin. Bol.*, **2004**, *2*, pp. 89-110.
[57] N. Stensen, *Canis Carchariae*, in ref. 1 (K&M), p. 585.
[58] G. Scherz, in ref. 1 (K&M), pp. 137-140.
[59] The association of fossil shark teeth with seashells was also described in Fabio Colonna's *De Glossopetris Dissertatio*: ref. 10. M. Rudwick, ref. 13, pp. 42-44; N. Morello, ref. 39, p. 71.
[60] Michele Mercati (1541-1593) and his teacher Andrea Cesalpino (1519-1603) were leading figures in late Renaissance study of *res metallica*. Cesalpino ordered the Medicean collection of natural history and completed Mercati's systematic work in *De Metallicis* (1596). See U. Viviani, *Vita ed opere di Andrea Cesalpino*, Viviani, Arezzo, **1917**, pp. 186-187, 218-219; B. Accordi, *Geologica Romana*, **1980**, *19*, pp. 1-50; P. Findlen, in ref. 4, pp. 61, 233-235; for the Medicean gallery of natural history in Pisa, certainly visited by Steno already during the first part of his stay, see L. Tongiorgi Tomasi, *Giardino dei Semplici. L'Orto Botanico di Pisa dal XVI al XX secolo* (Eds.: F. Garbi, L. Tongiorgi Tomasi, A. Tosi), Pacini, Ospedaletto, **1986**, pp. 161-170.
[61] J. Bek-Thomsen, in ref. 2 (A&L), pp. 233-258.
[62] N. Stensen, *Canis Carchariae*, in ref. 1 (K&M), p. 572
[63] E. Cioppi, S. Dominici, in *Water as microscope of nature. Leonardo da Vinci's Leicester Codex* (Ed.: P. Galluzzi), Firenze, Giunti, **2018**, pp. 171-183.

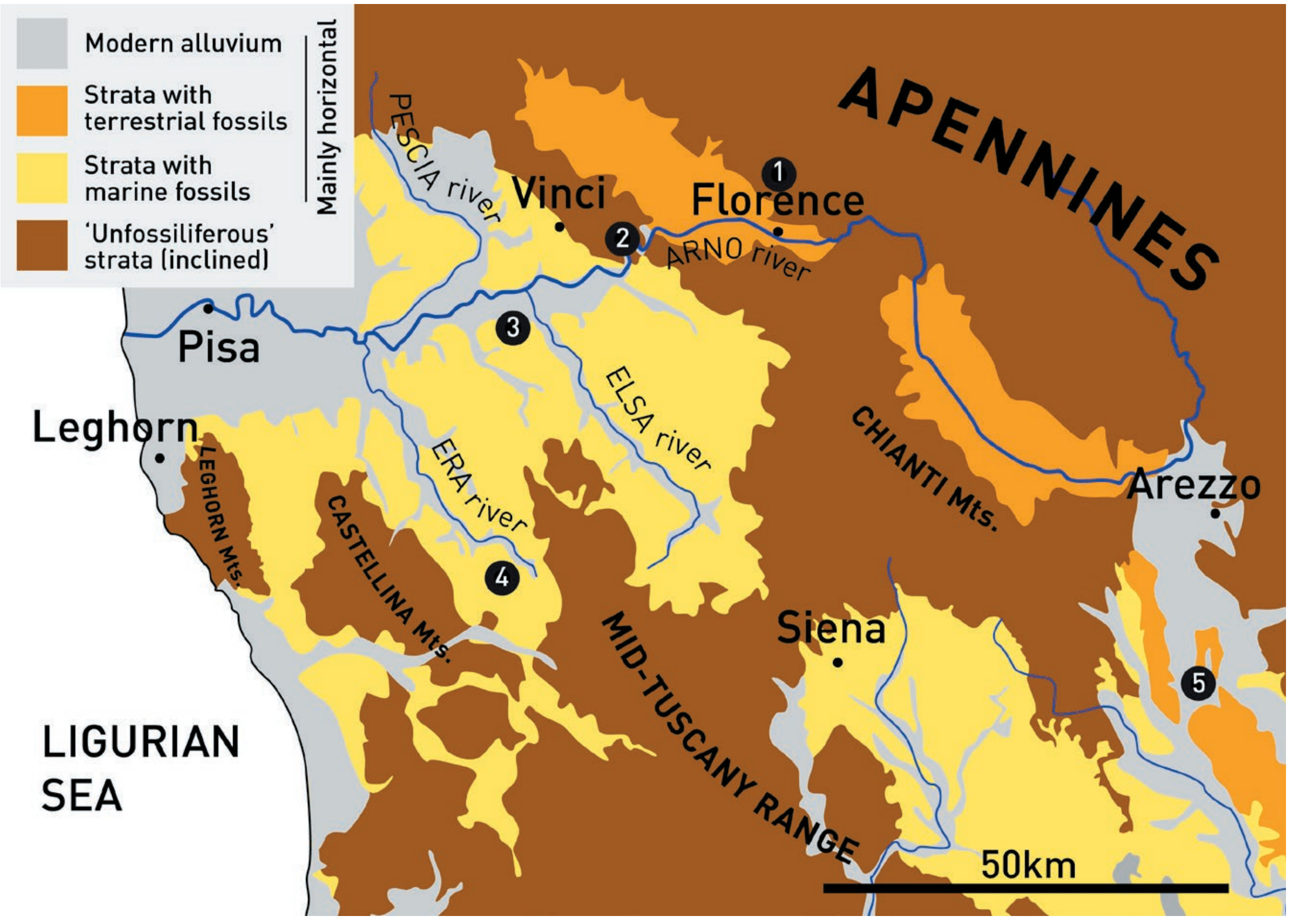

Figure 1. Schematic map of Tuscany showing localities mentioned in the present paper, in relationship with Steno's *Prodromus* description of strata on which he based his history of the Earth. These localities are: 1) Monte Ceceri, 2) Gonfolina, 3) San Miniato, 4) Volterra, 5) Chiana Valley. Original graphic by the author.

drawings that were engraved, together with all other plates, by the German artist Anton Eisenhoit (1553-1603). One type belonged to large sharks which we now know as the great white (*Carcharodon carcharias*), as the one dissected by Steno. In the words of Mercati:

> *I received very beautiful* [large tongue stones] *from my father, fortuitously found in a field near San Miniato.* […] *Ostracites* [fossil oysters] *are found in fields near the towns of Siena and San Miniato.*[64]

Evidence is thus consistent with an hypothesis that Steno studied fossiliferous strata of Tuscany early in 1666. Consequently, when he had an opportunity to dissect the head of a shark, his mind was already set. This explains the rapidity with which he published, hastening to secure a priority on the subject. At San Miniato he would also observe sandy and clayey strata, some cemented, most simply compacted, crop out in the steep flanks of the hill where the town is built. These strata are slightly inclined towards NNE (Fig. 3), so this is one of those places, in which he would have seen 'that the said soil is composed of layers superimposed on each other at an angle to the horizon' (see note 52 above), meaning they had been tilted after deposition.

The study of sedimentary strata allowed Steno to prove that water twice covered the Tuscan relief, acknowledging that observation of nature and words in Scripture work in pair:

> *Nor can there be strong opposition to the belief that the said soil was once covered with water.* […] [If] *we assume that this piece of ground always had the same situation,*

[64] M. Mercati, *Michaelis Mercati Samminiatensis Metallotheca: opus posthumum, auctoritate & munificentia Clementis undecimi pontificis maximi e tenebris in lucem eductum: opera autem & studio Joannis Mariæ Lancisii archiatri pontificii illustratum*, Roma, Salvioni, **1717** [1593], p. 48.

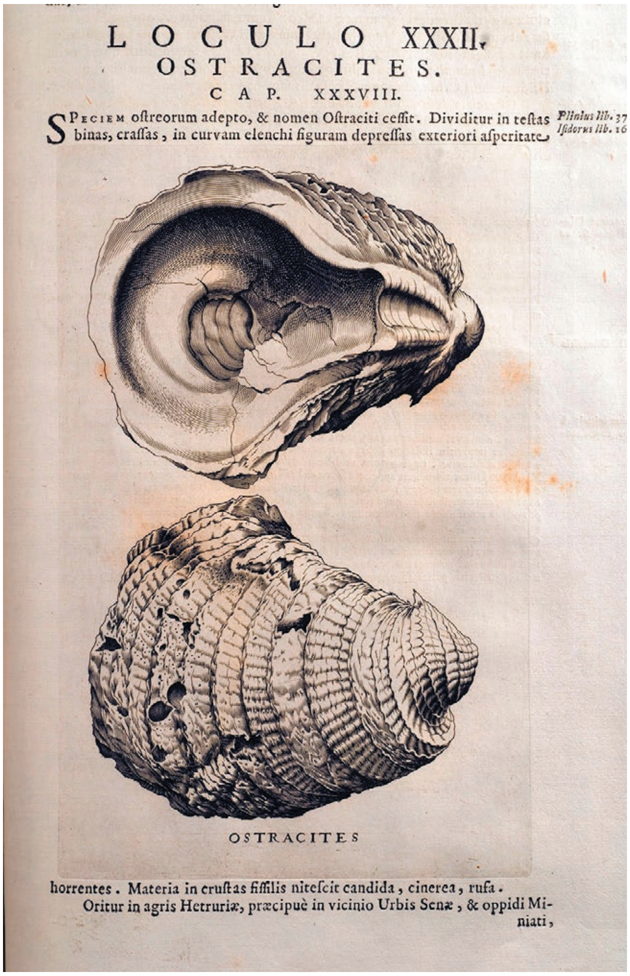

Figure 2. Copper engraving by Eisenhoit of a large oyster shell ('Ostracites') dug up from the earth at San Miniato ('oppidi Miniati'; locality 3 in Fig. 1) and drawn by Mercati, published posthumously in 1717, but available to Steno in 1666. Photograph by Saulo Bambi, reproduced with permission, courtesy of the Botanical Library of the Florence University.

> […] *we learn from Holy Scripture that all things, both at the beginning of creation, and at the time of the Flood, were covered with water.*[65] *Tertullian writes elegantly about this: "A change occurred in the whole world when it was covered with all the waters; even now, sea shells of mussel and whelk range over the mountains seeking to prove to Plato that the very peaks have been under water.*[66]

Steno's digression in *Canis Carchariae* revolves around the demonstration of the marine origin of fossils (he explains this through "conjectures" numbered 1-4, 6)

Figure 3. Slightly inclined fossiliferous strata at San Miniato (locality 3 in Fig. 1; outcrop about 50 m-thick). Rich shell beds associated with large shark teeth have been studied here since the time of Leonardo da Vinci (1453-1519) to the present day. Photograph by the author.

and the precipitation of solids from liquids (conjectures 4-5, indicating 'the ways in which solid bodies hidden in water may be secreted'). Judging from the subsequent development of these two topics in the *Prodromus*, this means that in 1666 not only had Steno already studied fossiliferous mudstones and sandstones at the top of the Tuscan sedimentary succession (his evidence of 'the Flood'), but also older unfossiliferous strata which he thought formed at 'the beginning of creation' (see above, and note 65), when God separated earth from a primordial fluid.

4. THE ITALIAN NETWORK

In 1667 Steno shared his thoughts on fossils with other learned men around him, not just on marine fossils, but also terrestrial ones. The latter were related to a 'time of giants' referrable to Scripture, a third biblical event with which to compare the fossil record, as it will be shown. The Book of Genesis in fact revealed that:

> *The giants were in the earth in those days, and also after that, when God's sons were being entered toward the daughters of humans and they were begetting to themselves; those were the giants from the eons [greek* αἰών*] the humans of renown.*[67]

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[65] N. Stensen, *Canis Carchariae*, in ref. 1 (K&M), p. 587. Morello, ref. 39, p. 77.

[66] N. Stensen, *Canis Carchariae*, in ref. 1 (K&M), p. 587.

[67] Genesis 6, 4, from the Greek Septuagint Bible. See R. S. Hendel, "Of demigods and the Deluge: toward an interpretation of Genesis 6:1-4", *J. Bibl. Lit.* 106, **1987**, pp. 13-26. For an exploration of Protestant and Catholic attitudes towards the interpretation of this passage, see A. Hessayon, ref. 6, pp. 5-40.

In Florence Steno was sustained by the esteem of newly-acquired learned friends, including renowned disciples of Galileo such as Vincenzo Viviani (1622-1703) and Francesco Redi (1626-1697).[68] The sea of Tuscan coast offered plenty of living shelled marine animals to compare with fossils that were dug up in nearby hills. Bruno della Molara, a member of the court, testified that in the summer of 1667 Steno was studying living mussels and discussing his view with others:

> *I am delighted by your progresses in the investigations of interesting matters, particularly of the mussels and I am even more pleased that you have made satisfactory observations which confirm your view.*[69]

Among the Florentine academians was Giovanni Alfonso Borelli (1608-1679), one of the most gifted disciples of Galileo Galilei.[70] The least friendly among the Medici courtiers, he helped Steno, providing knowledge and fossils form Sicily. Steno had contacted him soon after his arrival in Tuscany, as a suspicious Borelli revealed in July 1667 in a letter to Marcello Malpighi (of the same Galilean circle):

> *I'm giving you the news that Steno is here, and that he shall remain the whole summer, and that he told me he wants to come to visit me, and that he wants me to teach him something about geometry etc. I won't refrain from offering him all the courtesy possible, but I'm not so gullible as to believe in the idea of modesty and good manners in which he is proclaimed, because those little epistles he has printed clearly hint at his avidity to absorb all the things, and put others in distress, and I know these foreigners come here to us well prepared, and willing to remain cautious, so that their cunning by far surpasses ours, with the result that in the end it will be us who will be submitted for long.*[71]

The Italian network of learned men interested in Steno's *Canis Carchariae* included Agostino Scilla in Sicily,[72] collaborating with Borelli, Malpighi and John Ray,[73] and the physician Giovanni Battista Capucci from Crotone, in Calabria.[74] The authority of Prince Leopold, accompanied by the general enthusiastic acceptance of Steno by the Medici Court, forced Borelli to submit and provide specimens from Sicily. In August he answered the Prince:

> *I send you two chunks of stone of the type produced by date shells* [rock-boring mussels; …] *I've commanded to bring you some piece of good stone, which no doubt will give the opportunity to philosophise.*[75]

In two letters of October-December 1667, Borelli communicated with Prince Leopold about the interpretation of marine and terrestrial fossils. These manuscripts not only testified to the whole court being involved in Steno's research, but particularly revealed that larger fossil bones were interpreted as evidence of 'a time of giants', as mentioned in the Book of Genesis:

> *I also thought that those shells could have originated from the sea, but then I changed opinion. I will await for the fine discourses of these Gentlemen to ascertain for me the truth. In the meanwhile, I have written to friends in Palermo, Siracusa and other places to get me the so called Giants' teeth, and those large petrified shells that are found at many places in Sicily* […] *If Your Highness could send me the drawing of the skull of that African ox found in the Chiane* [referring to the Chiana valley, locality 5 in Fig. 1] *to know how big it is, I would be grateful.* […] *I will send to Livorno those teeth and shells that I am collecting.*[76]
> *I have received the drawing of the buffalo skull, or ox found in the Chiane, and it is indeed much larger than those that we see nowadays in Italy* [see Fig. 4 for a similar fossil coming from the same context]. *If it came from Africa I couldn't say, since I'm told that in that savage place you don't find oxen of such an enormous size. Maybe in that time in Italy lived that race of a size larger than our* [cattle] *given that as among both dogs and horses we find some that by large exceed others, and I can assure Your Highness that here we find certain limestones and human teeth the size of which must relate to a man at least 2.3 m tall. For you to get the exact proportion, I send with this letter a drawing of one of those teeth. The man who owns them is too jealous of these curiosities and I didn't dare ask, even if he is a friend. I have moreover collected a large quantity of petrified shells, some of very large size, that I will send, as you commanded me to do, with the first vessel that sails*

[68] P. Galluzzi, in ref. 39 (Negri, Morello, Galluzzi), pp. 113-129.

[69] For Bruno della Molara (1639-1685) see A. Cont, *Dimensioni e problemi della ricerca storica*, **2011**, *2*, pp. 231-259. Letter (14 July 1667) quoted in ref. 1 (K&M), p. 187. Another learned informant was Francesco Maria Florentini (1603-1673): G. Scherz, in ref. 1 (K&M), p. 182.

[70] L. Boschiero, in *Borelli's On the movement of animals - On the force of percussion* (Tr.: P. Maquet), Brill, Leiden, **1989**, p. i-xxi. P. Galluzzi, ref. 68.

[71] G. A. Borelli, 17 July 1666, in M. Malpighi, *The correspondance of Marcello Malpighi* (Ed.: H. B. Adelmann), Cornell University Press, Ithaca-London, **1975**, 1, pp. 318-319. Borelli was studying animal movement, a subject dealt with by Steno at exactly the same time.

[72] F. Giallombardo, *Agostino Scilla (1629-1700) e la cultura visuale della historia, fra antiquaria e storia naturale*, unpublished PhD thesis, Università di Palermo, Palermo, **2016**, pp. 71-72.

[73] P. Findlen, *Science in the age of baroque* (Eds. G. Gal, R. Chen-Morris), Springer, Dordrecht, **2013**, p. 135.

[74] G. B. Capucci, 25 July 1667, in ref. 40, pp. 352-352.

[75] G. A. Borelli to Prince Leopold, 3 August 1667, in ref. 38 (MG), Gal. 278, f. 42v.

[76] G. A. Borelli to Prince Leopold, 4 October 1667, in ref. 38 (MG), Gal. 278, f. 73r-73v.

Figure 4. Skull of a large ox dug up in Val di Chiana (width of horns about 105 cm); a similar specimen is mentioned by Borelli in letters to Prince Leopold. Photograph by Saulo Bambi, specimen reproduced courtesy of the Museum of Natural History, University of Florence.

Figure 5. Malta 'large tongue stones' (in the terminology used in 1667) from unspecified 'Old Museum collection' (= '*Antica Collez. del Museo*', written in the 19th century): similar specimens were sent by Borelli in 1667. Photograph by Saulo Bambi, specimen reproduced courtesy of the Museum of Natural History, University of Florence.

> *to Livorno. When Mr. Steno will pass from here, I will see him and gladly serve him.*[77]

The finding of fossils of 'a man at least 2.3 m tall' and the bones of animals larger than the modern certainly solicited Steno's philosophical interest for links between observation of nature and Scripture. In July 1668, Borelli informed the Prince that the vessel with its naturalistic cargo had shipwrecked and that he provided a new collection of fossils. Similarly to the first shipment, it included 'stones taken from mountains twenty miles far from the sea'[78] and other geological specimens. Clearly, there was a keen interest for fossils at the Medici court in connection with Steno's activities of 1667.

> *Specimens from Malta are not all wrapped in their stoney casing, but imagine them to be* [originally] *contained in the same soft stone in which you see the tongue stones, or teeth; these teeth, vertebrae and eyes are dispersed in black stone, some small some large* [see Fig. 5] *Such observations, and better ones, will be made over there by those illustrious philosophers, being myself humbly busy with laying down this book of mine on paper, in the hope to complete it in short time.*[79]

We thus know that, at least since summer 1667 and while working at a larger dissertation on solids naturally enclosed in other solids, Steno involved a group of informed people in a fervent activity directed towards definitely proving that fossil shells and 'tongue stones' did not form inside the rocks, and thus verified their utility as a means to 'philosophise' on historical events. We can also reasonably speculate that 'philosophising' included a discussion of matters distinctly related with biblical events: remains of large terrestrial animals of African affinity provided information on a 'time of giants', while marine fossils, whether from Malta, Sicily or Tuscany, would mark the time when waters covered the land, ending the existence of 'those races of a size larger than ours' – in Borelli's words.

5. EARTH'S HISTORY UNROLLED IN TUSCANY

In May 1668 Steno had informed Magalotti about his intention to complete a 'treatise on the earth and the bodies found in it', described as 'a succinct, not to say disordered, account of the chief things that I have resolved to set down in the Dissertation itself, not only more distinctly, but also at greater length, with in addition, a description of the places where I have observed each item'. The final text was completed in August 1668[80] after months of additional fieldwork traveling 'from the Arno to the Tiber' (that is, from Florence to Rome: he apparently never suceeded in moving farther south).

The *Prodromus* addressed some of the basic questions of natural philosophy: what is the nature of matter, what is movement, and what is the method to answer

[77] G. A. Borelli to Prince Leopold, 1 December 1667, in ref. 38 (MG), Gal. 278, f. 95r-95v.
[78] G. A. Borelli in ref. 38 (MG), Gal. 278, f. 95r-95v.
[79] G. A. Borelli to Prince Leopold, 8 July 1668, in ref. 38 (MG), Gal. 278, 195r-195v.

[80] G. Scherz, in ref. 1 (K&M), p. 209.

these questions? More importantly, Steno took a clear position regarding Earth's history, choosing the universal flood as the fulcrum of the discourse, the occurrence of which he could now clearly demonstrate. As far as the nature of Tuscany allowed, Steno's method presented evidence of the other biblical events mentioned above, one concerning the third day of creation, when the Aristotelian element earth started to exist separated from water, another concerning the time when giants populated the Earth. To these he added in the *Prodromus* a further biblical event, the repopulation of the planet, occurring after the deluge had swept away "all things which have the breath of life, and whatever was on the dry land" (Gen 7, 22). This repopulation, starting from a handful of noachian survivors, soon spread all over the world following God's command ("increase and multiply, and fill the earth and have dominion over it": Gen 9, 1). Evidences of this were represented by the ruins of ancient civilizations, from the Etruscan in Tuscany, studied by Steno's contemporary antiquarians and briefly presented in the *Prodromus*, to the Chinese in the Far East, then made popular by Martini's chronicles (see above notes 40-41).

The first part of the book is methodological, abstract and complex, but worth the effort of reading – implies its author – because it promises to solve a problem of natural philosophy that troubled contemporary authors: 'namely the way in which marine objects had been left in places far from the sea', a problem concerning 'a kind of universal deluge' (p. 6).[81] In the first part of the book (pp. 6-23), Steno presented a new category of phenomena, 'solids naturally contained in other solids',[82] bringing order to observations of different kinds:

> *If one wishes to reduce solids enclosed naturally within solids to definite classes, by the above method, some of them will be found to have been produced by apposition from an external fluid, this refers either to sediments such as the strata of the earth […] or angular bodies […]. Other solids are produced through apposition from an internal fluid.' […] 'it will be easy, given the solid and its location, to make a definite statement about the place of its production.* (p. 23)[83]

The *Prodromus* then considered specific classes of solids, including 'strata of the earth' (pp. 26-28), explaining the historical meaning of the regularly-stacked bodies of turbidite sandstones that form large part of the Apennines. These are sedimentary strata characterised

Figure 6. Inclined, unfossiliferous strata of 'Macigno' sandstone at the historical Monte Ceceri quarries (outcrop about 20 m-thick, locality 1 in Fig. 1; similar strata occurred at the Gonfolina quarries, locality 2 in Fig. 1). Strata are bounded by surfaces that once were 'parallel to the horizon', to use Steno's words (*Canis carchariae dissectum caput*, written in 1666). Photograph by the author.

by sharp or erosive bases, tabular geometry (Fig. 6), good-sorting of the clastic component and sedimentary structures that indicate settling of particles while the water mass was still moving (Fig. 7). To Steno they were documents of the third day of creation, immediately before the separation of dry land from sea and when a 'universal fluid' was all that there was.

> *Differences in layers at the same place can be produced either by the diversity of particles leaving the fluid in succession, as this fluid is gradually dissipated more and more, or by different fluids being conveyed there at different times: so it happens that sometimes the same arrangement of layers is repeated in the same place, and often evident signs exist showing the ingress of new material.* (p. 26)
> *If all particles in a stony stratum are observed to be of the same nature and of fine size, it cannot reasonably be denied that this stratum was produced at the time of Creation from a fluid that then covered all things; Descartes, too, accounts for the origin of the earth's strata in this way.* (p. 28)[84]

The significance of these primordial strata is enriched by their association with widely-separated 'high mountains' (the Apennines). This fact proved that on the dawn of the third day of creation a fluid covered all things, as explained at the end of the book:

> *That there was aqueous fluid, however, at a time when animals and plants had not yet appeared, and that the fluid*

[81] Numbers in brackets refer to pages in the original 1669 publication, translated in ref. 1 (K&M), pp. 621-660.
[82] N. Morello, ref. 39, p. 79-80.
[83] N. Stensen, *Prodromus*, in ref. 1 (K&M), pp. 632-633.
[84] N. Stensen, *Prodromus*, in ref. 1 (K&M), pp. 635. Steno refers to René Descartes' *Principia Philosophiae* (1644), containing rather a model of the Earth, than an account of its history: see M. J. S. Rudwick, ref. 7, pp. 55-59.

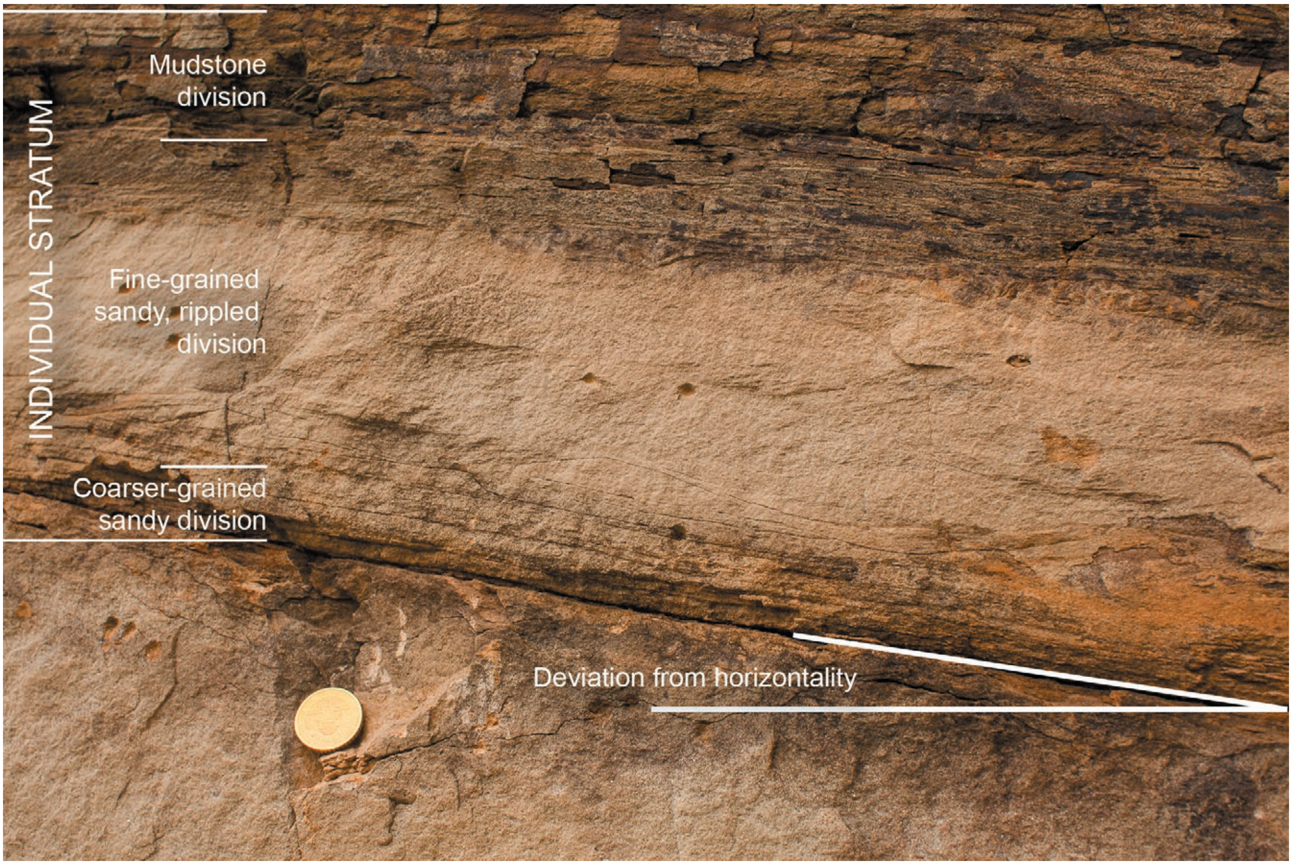

Figure 7. Turbidite sandstone of the Macigno Fm (detail of one of the strata in Fig. 6), showing sedimentary structures (Monte Ceceri quarries, near Fiesole; locality 1 in Fig. 1; coin for scale: 22 mm). Finer-grained particles have settled above coarse-grained ones as a fluid transports them in ripples, in light colour, finally giving way to mud deposition, in dark colour. Stratal surfaces are parallel one to another (Fig. 6), but all are inclined with respect to the horizontal, meaning they have been titlted after their deposition. Photograph by the author.

> *covered everything, is proved conclusively by the strata of the higher mountains which are free from all heterogeneous material; the outline of these strata testifies to the presence of a fluid; their material bears witness to the absence of heterogeneous bodies; the similarity in materials and outlines of strata from different mountains that are widely separated proves indeed that the fluid was universal.* (p. 73)[85]

By 'heterogeneous material' he meant the petrified remains of ancient living beings (see below). All three passages stress sorting of the particles that form the sedimentary bed and their origin by settling from a fluid (Fig. 7). An explanation of their actual position on 'higher mountains' as the key to infer the universality of the primordial fluid, had been anticipated in *Canis Carchariae* (without specifying if in relation to the first flood, when solid matter separated from the universal fluid, or the second universal flood, when all breathing creatures living on land were wiped out) where earthquakes had been called into action:

> *No weight should be attached to the arguments set out by people when they say that bodies of this kind ought to be found everywhere if they owe their existence to the waters covering all places, or at least, that such bodies when found, should not be found only in high places. [...] It would be easy, to show how great are the changes in soil caused frequently by earth movement.*[86]

Other classes of solids included 'mountains' (pp. 32-34) and 'angular bodies', or crystals in modern terms. Here he informs us that 'the majority of the minerals with which human effort is engaged did not exist from the beginning of things' (p. 44). By exclusion, the third day of creation, when solid earth first formed, is still documented in the natural world by some surviv-

[85] N. Stensen, *Prodromus*, in ref. 1 (K&M), p. 654.

[86] N. Stensen, *Canis Carchariae*, in ref. 1 (K&M), p. 587-588.

ing mineral. He was possibly thinking of the minutest clasts that make up turbidite sandstones of the Appennines – although no evidence of this thought exists, but of course not including the largest and youngest crystals quarried at that time in Tuscany. For their size, these formed the object of Steno's long discussion of geometric properties of regular solids, in pages that have attracted the attention of historians of mineralogy and which formed a long digression in the central part of the book (pp. 37-53).

Also at the core of the book (pp. 53-61) is the discourse on organic fossils. Evidence of their marine origin included a comparison between modern animals and fossils he had seen in Tuscany, including Borelli's specimens, with fossils embedded in their matrix. Steno's 1666 interest in demonstrating that glossopetrae were shark teeth is not repeated in the *Prodromus*. Their heuristic role as proof of the marine origin of the sediments in which they were found, hence proof of the biblical flood, is completely substituted in the *Prodromus* by the much more ubiquitous shelled molluscs. Examples abound, while he recalls shark's teeth only in passing:

> *There are shells of oysters, of remarkable size, in which are found several oblong, worm-eaten cavities* [Fig. 2] *in all respects similar to those that are inhabited by a certain type of shellfish in the rocks of Ancona, Naples and Sicily.* […] *In lumps of earth brought here from Malta, besides various teeth from various sharks, are found also various shellfish, so that if the number of teeth persuades us to ascribe their production to the earth, the construction of the teeth and their abundance in each animal, the similarity of the earth to the sea bed, and the other marine bodies found in the same place favour the opposite opinion.*[87]

Then he turns to remains of terrestrial animals and affirms his trust on the biblical account of the same evidence:

> *For others, difficulty arises from the size of the femurs, crania, teeth, and other bones that are dug from the earth; but there is not much either in this objection that unusual size should suggest a method beyond the powers of nature, since:*
> *1. In our age, men of very large stature have been observed.*
> *2. It is certain that there existed at one time men of gigantic size.*
> *3. Often the bones of other animals are mistaken for the bones of human beings.*
> *4. To attribute to nature the production of truly fibrous bones is on a par with saying that nature can produce the hand of a man without the remainder of the man.* (p. 62)

The statement 'It is certain that there existed at one time men of gigantic size' is a reference to Borelli's gigantic 'human teeth' and to the 'time of giants' narrated in Genesis 6, 1-4 – again, Steno obviously had the Bible in mind – while his familiarity with fossil bones and teeth of terrestrial animals echoes Borelli's inputs on the lack of modern analogues of the bones of the 'Chiana' gigantic ox (Fig. 4) and other large animals. In analogy with marine remains, terrestrial ones (including plants, pp. 65-67) were associated with fluvial conglomerates. These abound in the upper Arno valley and other places between Florence and Arezzo (for example locality 5 in Fig. 1) and prompted yet another vision of solid particles moved by a liquid.

> *The place from which the said bones are dug was built up from various strata that are filled with stones rolled down from the surrounding mountains by the force of torrents.* (p. 65)[88]

The series of proofs of the unrolling of events that match the biblical narrative is completed by the geological description of the hill upon which the town of Volterra is built (locality 4 in Fig. 1). In this section Steno merges observation of nature with antiquarianism and historical accounts, trusting the authority of classic authors, as he had done two years before in *Canis carchariae*. Most important, this is also the point he introduces absolute time in the narrative, adopting the language of the chronologists that measure the number of years that have elapsed between some key events, albeit in Steno this takes the form of rough estimates. It is worth recalling here the obvious, that the science of chronology was essentially biblical, although not only biblical, as exemplified by the *Prodromus* itself. Earth's history was only a few days longer that human history, but a sufficiently long stretch of time to fit all the events that mattered, according to an average 17th century thinker.[89]

> *There are those to whom the length of time seems to destroy the force of the remaining arguments, since there are no recollections in any age to confirm that floods have risen to the places where many marine bodies are found today, if the universal deluge is excepted, from which time it is estimated that 4000 years have elapsed up to the present.*[90]
> *It is certain that before the foundations of the city of Rome were laid, the city of Volterra was already powerful; but shellfish of every kind are found in the huge stones that are found in certain places there.* […] *The whole hill on which the oldest of the Etruscan cities is built rises from marine*

[87] N. Stensen, *Prodromus*, in ref. 1 (K&M), pp. 650-651.

[88] N. Stensen, *Prodromus*, in ref. 1 (K&M), p. 652.
[89] M. Rudwick, ref. 7, pp. 9-23; A. Grafton, ref. 41.
[90] N. Stensen, *Prodromus*, in ref. 1 (K&M), pp. 651-652.

sediments, laid on top of other, parallel to the horizon, in which there are many non-stony strata which abound in true molluscs that have suffered no change in any way, and so it is possible to say with certainty that the unchanged molluscs that are extracted from them today were produced more than 3000 years ago. From the founding of the city to the present day we reckon more than 2420 years have elapsed; and who will not grant that many centuries have elapsed since the first men transferred their homes there until it grew to the size that flourished at the time of the founding of the city? If we add to these centuries the time which elapsed between the laying down of the first sediment of the hill of Volterra and the withdrawal of the sea from the same hill, when strangers flocked to it, we shall easily go back to the time of the universal deluge. (p. 63-64)[91]

The final section of the *Prodromus* (pp. 67-76) strictly concerns the fit betwen events inductively demonstrated for Tuscany and those narrated in the Bible. They are preceded by a sentence that perhaps justified the opinion that Steno was aware of consequences from the Church: 'But lest anyone be afraid of the danger of novelty etc.' On the other hand, judging from the fact that for Steno biblical history was history *tout court*, these closing passages appear a summary of what he had finally proved, proud to announce the coherency of the marvellous plan of God. Their content had been forewarned in the introductory chapter:

The fourth part describes various conditions of Tuscany not dealt with by historians and writers on things of nature, and proposes a kind of universal deluge that is not rejected by the laws of natural movements. (p. 6)[92]

Accompanied by the now-famous schematic drawing of the six periods during which the present Tuscan relief took shape,[93] the final part of the *Prodromus* is a counterpoint between the voices of the scripture and nature, the former proposing, the latter answering (whenever possible), sometimes both remaining silent. Steno's discussion of his six periods revealed the final purpose of the dissertation and of all his commitment to the study of fossils, crystals and rocks, and retrospectively the climax of a lifetime search for truth: not to found a new science ('geology'), but to reconcile philosophy and theology, physics and metaphysics:

How the present state of anything discloses the past state of the same thing is made abundantly clear by the example of Tuscany, above all others. […] *With regard to the first aspect of the earth, scripture and nature agree in this respect, that everything was covered with water; but of how and when it began, and how long it lasted as such, nature says nothing, while scripture speaks.* […] *at the time when the strata of unmixed material, obvious in all mountains, were being formed, the rest of the strata did not yet exist, but everything was covered with a fluid devoid of plants, animals, and other solids. Since no one can deny that the strata are of the kind that could have been produced immediately by the First Mover, we recognize from this the obvious agreement between scripture and nature.* (p. 70)
About when and how the second aspect of the earth, which was flat and dry, began, nature is likewise silent, while scripture speaks […]
When the third aspect of the earth, which is believed to have been uneven, began, neither scripture nor nature determines; nature shows that the unevenness was of some magnitude; scripture, moreover, mentions mountains at the time of the deluge; as to the rest, neither scripture nor nature determine when those mountains, of which scripture makes mention, were produced […] *reason persuades us that, in the first centuries of the world's existence, cavities were gnawn out by water and by fire, so that slighter collapses of strata followed from this.* […]
The fourth aspect, when all was ocean, seems to cause more difficulty, although in truth it is not difficult. The production of hills from marine deposits testifies that the sea was higher than it is now, and this not only in Tuscany but also in very many places far enough from the sea […] *If the activity of a living creature can bring it about that sometimes places flooded with waters are made dry by its decision, and sometimes are flooded with new waters, why should we not willingly concede to the First Mover of all things the same freedom and the same powers? With regard to the time of the universal deluge, sacred History, reviewing everything in detail, is not opposed by secular history. The ancient cities of Tuscany, some of which are built on hills produced by the sea, were founded more than 3000 years ago; in Lydia, however, we come nearer to 4000, so that it is possible to reckon from this fact that the time at which the earth was abandoned by the sea is in accordance with the time of which scripture makes mention.* […] *nature does not contradict what scripture determines about how high the sea was.* (p. 72)[94]

Steno was finally asserting in the Latin language directed not just to his Italian readers, but to the whole European community of learned men, that a universal principle of geometry, perfectly entrenched in the new philosophy, confirmed biblical facts. This would have helped to silence unorthodox thinkers and re-assert the supremacy of a literal reading of the biblical text. If Steno's sensibility had been shaken by criticism towards standard chronology, alive in certain cultural circles,

[91] N. Stensen, *Prodromus*, in ref. 1 (K&M), pp. 651-652.
[92] N. Stensen, *Prodromus*, in ref. 1 (K&M), p. 625.
[93] S. J. Gould, *Hen's Teeth and Horse's Toes: Further Reflections in Natural History*. New York, Norton **1983**, 413 pp.
[94] N. Stensen, *Prodromus*, in ref. 1 (K&M), pp. 653-655.

biblical references in the *Prodromus* were more than a tribute to religion by a Catholic convert. They formed instead the conclusion of a philosophical and theological journey in the search for 'true religion' that had commenced before travelling to Tuscany. His reasoning gave a final sense to a long study to find the meaning of fossils shells and 'tongue stones'.

6. AFTER THE PRODROMUS

In the same year of the publication of the *Prodromus*, Steno continued to carry out geological fieldwork in the light of his theory, as testified by a letter written in October 1669 after visiting quarries in Hungary (present day Slovakia), a new occasion to study the rocks produced during the time of the first 'universal fluid'.

> *My journey to visit the quarries caused me great happiness not just for the novelty of the observations, which were very few, but for the autopsy of those things, that upon reading metallic authors are understood with much difficulty. I have seen nonetheless something consistent with my opinions on the transformations that the earth underwent, inasmuch that in the same places soils of* Macigno *are inclined with respect to the horizon, so that in that place cannot have been materially made.*[95]

The letter proves that the method exposed in the *Prodromus*, nicely expressed with borrowed words from the anatomist ('the autopsy of those things'), was once again applied with success, this time to strata observed outside of Italy.

The science inaugurated by Steno relied on the observation of nature and on concordance with Scripture. The attempt at reconciling inconstistencies occupied learned men[96] and missionaries, particularly among the Jesuits including in 1667 Athanasius Kircher.[97] Debates such as this continued into the eighteenth century, while a steadiliy increasing number of *savants* across Europe presented new theories of the Earth, and skepticism towards biblical chronology reached further.[98] Earth as sketched in the *Prodromus* looked much like the model introduced by Descartes in his *Principiae Philosophiae* of 1644, with its inner cavities justifying the collapse of originally-concentric sedimentary strata at its surface.[99] But Descartes despised history,[100] while Steno searched different sources, both textual and natural, the latter based on geometry. Few contemporary natural philosophers were equipped with Steno's experience of the natural world, many distintly favouring the study of annals and biblical scholarship, with a penchant for establishing systems often disconnected from empirical evidence. Despite not having Steno's experience in the natural world, most still accepted Scripture and classic authors as trustworthy sources.

Among contemporary authors, the Sicilian painter Agostino Scilla (1639-1700; see above note 72) had studied a very large variety of marine fossils and their sedimentary context, as he demonstrated in his *La Vana Speculazione Disingannata dal Senso* of 1670. Himself creator of the wonderful engravings that illustrated his book, rivalling those of Eisenhoit used by Steno, Scilla did not cite the Dane. However, he surely knew *Canis Carchariae* through Borelli and Malpighi, academicians with whom he was connected in Sicily. Similarly to Steno, Scilla interpreted marine fossils as evidence of the biblical deluge, seeking further evidence for his interpretations in the work of classical authors and antiquarians.[101]

Robert Hooke (1735-1703)[102] authored a rudimentary theory of the Earth in 1668 based on Steno's hypothesis of 1667 that most fossils originated in the sea, but dismissing the Flood as the cause, invoking in its place the action of earthquakes. The latter he called into action, together with other natural causes, to also explain other biblical episodes, such as the time of giants, while paying close attention to contemporary biblical scolarship.[103] In his 1715 theory of the Earth, the astronomer Edmond Halley (1656–1742), of the same Baconian circle as Hooke, still relied on chronology in Genesis, however more critically interpreted.[104]

Steno's lesson certainly informed the other great contemporary philosopher and pioneer in the study of the Earth, the German polymath Gottfried Wilhelm

[95] N. Stensen to M. Malpighi, 27 October 1669, in ref. 40 (Adelman), p. 429-430. 'Metallic authors' referred to the work of late Renaissance learned men like Michele Mercati. 'Macigno' refers to a particular type of sandstone quarried near Florence. This is devoid of fossils and thence to Steno it is the material evidence of the third day of Creation.

[96] Debates among Protestants in the Dutch Republic were fierce, while chronologists contemporary to Steno investigated "the nature of ancient and modern, eastern and western calendars and established the dates of great events": A. Grafton, ref. 41, p. 45.

[97] R. Rappaport, ref. 5, pp. 77-79. A. Ziggelaar in ref. 2 (Rosenberg), p. 140.

[98] R. H. Popkin, A. J. Vanderjagt, *Scepticism and irreligion in the seventeenth and eighteenth centuries*, Brill, Leiden, **1993**, 373 p.

[99] M. J. S. Rudwick, ref. 7, pp. 55-56.

[100] R. Rappaport, ref. 5, pp. 64-65; M. J. S. Rudwick, ref. 7, p. 55.

[101] P. Findlen, ref. 73, pp. 119-159.

[102] British natural philosopher, active in Montpellier at the time of Steno's residence there, and one of the founding members of the Royal Society in London, Hooke deciphered the organic origin of fossils as early as 1663, publishing the idea in his *Micrographia* (1665): T. Yamada, in ref. 2 (Rosenberg), pp. 107–126.

[103] W. Poole, ref. 4, pp. 43-49; K. Birkett, D. Oldroyd, *The Uses of Antiquity* (Ed. S. Gaukroger), Springer, Dordrecht, **1991**, pp. 145 – 170.

[104] W. Poole, ref. 4, pp. 45-46.

Leibniz (1646-1716). Leibniz had met Steno more than once between 1677-1680 and the history of the world, the main theme of the *Protogaea* that the German would complete in 1693, formed the object of their discussion. Leibniz, deeply influenced by the Dane,[105] left the clearest testimony of the primary significance that the full *Dissertation on solids* was meant to have for contemporary philosophers:

> *I have often incited him* [Steno] *further to carry them out* [geological studies] *and to draw from them conclusions to find out the origin of the human kind, the general water flood and some other nice truths which would confirm what the Holy Scripture tells of that.*[106]

All of the above authors, and others, were evidently influenced by Steno. With them, evidence that biblical scolarship genuinelly informed the work of early modern men of science is therefore ample. They were still natural philosophers, not geologists, but their science was for the first time driven by the observation of nature, to which they adapted the authority of preceding authors. In this important phase of the history that eventually led to modern geology during the last quarter of the eighteenth century,[107] Steno was the first to publish a history of the Earth based on the study of fossils and sedimentary strata, albeit in the summary form to which he felt pressed by a variety of factors. We can still comment on today the fact that Steno accepted an age of the Earth inconceivable by modern standards, but this should in no way influence our understanding of his role in the history of science.

7. CONCLUSIONS

Nicolaus Steno's contribution on the study of the Earth, passed on to us through two published essays of 1667 and 1669, looks to the relationship with contemporary culture and with the transnational society of learned men to which he belonged. Steno and his contemporaries shared the belief that the Bible was an historical book, and that the Book of Genesis constituted a means to learn about the early part of Earth's history. Steno thought that his work as a natural philosopher could find in nature evidence for the mysteries of creation. It is evident that Steno took Scripture as a guide to comprehend the structure and composition of the earth beginning with his student years in Copenhagen, Amsterdam, and Leiden, in his subsequent explorations of the Tuscan region, and in his readings of and interactions with fellow natural philosophers at the Medici Court. In Tuscany he perfected a method that allowed him to reconstruct historical events independently, but consistently with Scripture. This method was based on the application of simple geometric principles to the study of different types of geological objects, from crystals and fossils, to rocks and strata, and on to mountains and the whole Earth. Evidence in his writings from 1659-1669 is consistent with an interest to carry out an anatomy of the Earth nurtured through the years, partly hidden by the primary interest in the anatomy of animal and human bodies.[108] It is also hypothesised that this was one of the reasons for travelling to Tuscany where he could carry out the necessary field work within the right cultural milieu. Steno was a meditative man whose anatomical studies had significance inasmuch they disclosed the immense wisdom displayed by God in creating the world. The consistency of his study of the Earth with the narrative of Scripture would have blunted criticism of the skeptics, reinforcing the authority of the Bible.

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[105] C. Cohen, A. Wakefield, *Protogaea*, by W.G. Leibniz, University of Chicago Press, Chicago & London, **2008**, pp. xiii-xlii.

[106] G. W. Leibniz, quoted in ref. 1 (K&M), p. 226; see also F. Sobiech, in ref. 2, p. 181; D. Garber, in ref. 13 (A&L).

[107] M. J. S. Rudwick, ref. 7, pp. 79-127.

[108] The connection between anatomy and the idea of landscape is explored by Rosenberg, G.D., "An artistic perspective on the continuity of space and the origin of modern geologic thought", *Earth Sciences History*, **2001**, *20*, 127-155; G. D. Rosenberg, "The measure of man and landscape in the Renaissance and Scientific Revolution", in *The Revolution in Geology from the Renaissance to the Enlightenment* (Ed.: G. D. Rosenberg), *Geol. Soc. Am. Mem.*, **2009**, *203*, 13-40.

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How do Crystals Grow? Steno's Approach

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Abstract. Steno (1638-1686) operated in a historical context rich in discoveries and observations done by previous scientists such as Vannoccio Biringucci, Georg Bauer (Agricola), Johannes von Kepler, Robert Hooke, Christiaan Huyghens, Erasmus Bartholin, and others. Steno also had to fight against some irreducible dogmatic and "mythological" beliefs, such as the *vis formativa* and *succus lapidescens*, supported by e.g. Michele Mercati and Anselmo Boetius de Boot, respectively. In *De solido intra solidum naturaliter contento dissertationis prodromus* Steno deals with almost all aspects of Earth Sciences and not just "solid inclusions" as it might seem from the full title of the *Prodromus*. This contribution deals only with aspects related to crystallography and minerals in general. The most famous is highlighted by the sentence "*non mutatis angulis*" which is a clear reference to the fact that interfacial angles of quartz crystals do not change regardless of the size and the number of the faces. This observation was then generalized as a law for all minerals by Jean-Baptiste Romé de l'Isle a century later. Less well known but of great importance is Steno's assertion that the crystals grow thanks to the addition of particles that come from an external fluid and are not "fed" from the inside like in vegetables; moreover, the speed of growth is not the same for all faces. For example, the faces of the "pyramid" in quartz can grow more or less rapidly than those of the prism (giving rise to either squat or elongated crystals). It can therefore be argued that Steno has greatly contributed to the concept of anisotropy in the solid state, typical of all crystals. Stenonite, $Sr_2Al(CO_3)F_5$, is a new mineral dedicated to his memory about sixty years ago.

Keywords: Steno, crystal growth, quartz, interfacial angles, stenonite.

INTRODUCTION

To introduce the topic of crystal growth and to highlight Steno's great contribution, it seems particularly fitting to report most of the first page from the foreword by O. Grubessi and F.P. Sassi,[1] of the book "Minerals in stamps" by Grubessi and Pasero, published by the Italian Society of Mineralogy and Petrology in 1998.

> *Special stones and gems have written the history of Earth Sciences, and have accompanied the history of man with variegated roles.*

[1] O. Grubessi, F.P. Sassi, in *Minerals in stamps* (Eds. O. Grubessi, M. Pasero), Felici Editore, Pisa, **1998**, viii +215 pp.

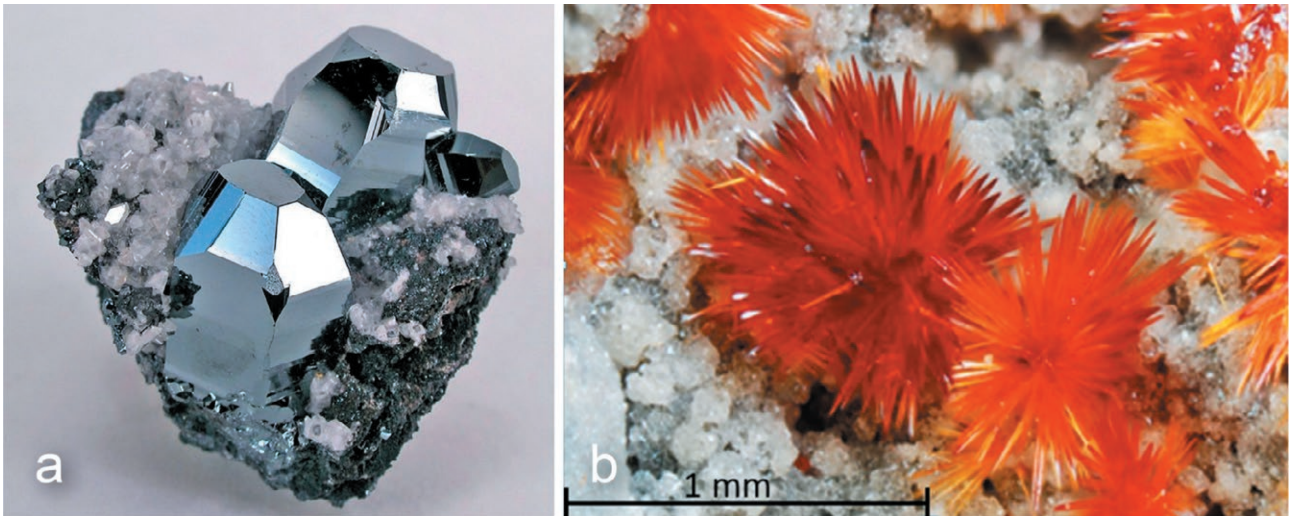

Fig. 1. Morphology and colour of minerals. 1a: Hematite Fe2O3 (https://www.mindat.org/photo-122270.html). 1b: Red and yellow crystals of cetineite [(K,Na)6Sb3+12(Sb3+S3)2O18(OH)0.5.5H2O] (Collection V. Paoletti, photo by B. Fassina, published with permission).

Charm, curiosity, magic, science; mystic therapy, magic therapy, physical therapy; belief in extra natural powers and the belief in the action of the product, are intimately bound with the role that stones, minerals and gems, play in our heritage as well as in the mentality of our ancestors.

By his nature, man has always been attracted by what is beautiful, precious and mysterious. Therefore, his interest in gems and minerals, which often have all these features, is not surprising.
In the course of centuries the intrinsic value attributed to these stones has also been modified as a result of external factors. Indeed, their rarity and beauty became supplemented on one side by their process, as an expression of human activity and intelligence, and on the other side, by their links with astrology and medicine, as an answer to transcendental requirements.
However, the attraction man has for minerals prevails over all the other features in human feelings, a kind of fascination which has not been the least extinguished by the development of scientific knowledge about their structure, properties, and genesis.

The well-shaped morphology, the beauty of minerals in general, the flatness and the shine of the faces (Fig. 1a), the color that can vary greatly even for the same species (Fig. 1b), were certainly some of the many observations on minerals that triggered human curiosity. While most people have limited themselves to expressing wonder and amazement, some have wondered what could be the source/origin of such peculiarities shown by natural objects. What are the relationships between what we can see with the naked eye and what is inside the crystal and which we cannot see? What are the reasons for the variability of shapes, color, luster, hardness? In conclusion, how do crystals form and grow?

When Steno lived in Tuscany he made many observations on the formation and growth of crystals as it can be understood from his *De solido intra solidum naturaliter contento dissertationis prodromus*.[2] Actually Steno was not the first one to deal with these problems, as reported in the next section where some of the pioneers of this long history will be mentioned.

THE BIRTH OF CRYSTALLOGRAPHY

In this brief historical excursus, the text by A. Authier[3], *Early Days of X-ray Crystallography*, published in 2013, to celebrate the international year of crystallography (2014), will be of great benefit.

By personal and perhaps questionable choice let's begin from the early 1500s, more precisely with Vannoccio Biringucci or Biringuccio (1480-1537) from Siena. Biringuccio was a great technician who strongly contributed to the literature related to mineralogy and metallurgy of the XVI century.

His work *De la Pirotechnia* (Fig. 2), written in Italian, was published posthumously in 1540. In the ten books that compose it, Biringuccio deals with minerals and mostly with melting, separating and alloying of

[2] N. Stenone, *Su un corpo solido contenuto naturalmente entro un altro solido. Prodromo a una dissertazione.* A cura di Annibale Mottana, Edizioni Teknos, Roma, **1995**, 66 p.
[3] A. Authier, *Early days of X-ray crystallography*, Oxford University Press, Oxford, **2013**, 464 p.

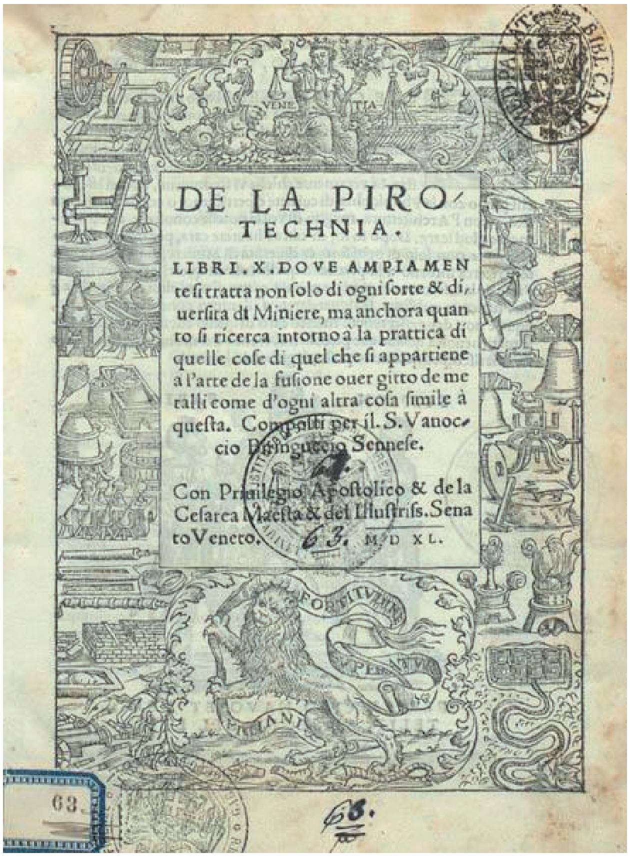
DE LA PIRO-
TECHNIA.
LIBRI.X.DOVE AMPIAMEN
te si tratta non solo di ogni sorte & di-
uersita di Miniere, ma anchora quan
to si ricerca intorno à la prattica di
quelle cose di quel che si appartiene
a l'arte de la fusione ouer gitto de me
talli come d'ogni altra cosa simile à
questa. Composti per il S. Vanoc-
cio Biringuccio Sennese.
Con Priuilegio Apostolico & de la
Cesarea Maesta & del Illustriss. Sena
to Veneto. M.D XL.

Fig. 2. Title page of *De la Pirotechnia*, published in Venice in 1540 (https://bibdig.museogalileo.it/Teca/ImageProvider?image=./000/000/302/302960/302960_00005r.jpg).

metals. *De la Pirotechnia*, repeatedly printed and translated into French, English, Spanish and German, had great success especially for its eminently practical aspect. As far as mineralogy and crystallography are concerned, we report (Biringucci[4], 1914 p. 187-188) his observation on the morphology of "margassite" (pyrite): "may be found as veins and in form of certain grains, either big or small, all cubic similar to dices, or alternatively prismatic all exactly squared so that no craftsman, with any instrument he uses, could not draw more perfect nor better their angles". In modern terms (see the Italian textbook Carobbi, Mineralogia, 1[5] p. 5) this sentence can be expressed as "pyrite occurs in crystals in the shape of a geometrically regular cube but also in the shape of a straight parallelepiped, with dihedral angles between pairs of faces always equal to 90°". As an example, Fig. 3a shows geometrically regular pyrite cubes with square faces, while in Fig. 3b the faces of the pyrite "cubes" are rectangles. But the interfacial angles are always 90°. As it is known, interfacial angles are important in crystallography but not the extension and regularity of the faces. This is the first qualitative reference to what will become the law of the constancy of interfacial angles expressed as a general law by Jean-Baptiste Romé de l'Isle in 1783. As we will see, Steno also contributed to this point.

Georg Bauer (1494-1555), a doctor, also read and appreciated Biringuccio's work. He is better known by the Latinized name Georgius Agricola. Agricola (Fig. 4) obtained the *Baccalaureus Artium* at the University of Leipzig and later studied medicine. He also studied at the Universities of Bologna and Padua and developed his interest in the mineral world especially during his stay as a doctor in the mining town of Joachimstal (Jáchymov, Bohemia) and later in Chemnitz, Saxony. He was a person of great culture who left several treatises written in Latin including:

- *Bermannus* (remarkable knowledge on mining), 1530.
- *De Natura fossilium* (systematic mineralogy work), 1546.
- *Rerum metallicarum interpretatio* (mineralogical glossary in Latin and German), 1546.
- *De re metallica*, 1556 (summa of the knowledge of the time in metallurgy and mining), which obscured the fame of Biringuccio's Pirotechnia.

Agricola is often considered the "father of mineralogy".

Interesting information on Biringuccio and Agricola and on the relationships between their works (De la Pirotechnia and De re Metallica) can be found in the paper *Origins of Mineralogy: the age of Agricola* by C. Schneer [6[6]].

Other contributors practically contemporary to Steno's *Prodromus* are discussed below.

Johannes Kepler (1571-1630), was the first to postulate a correlation between the external morphology and the internal structure of crystals. In his 24-page pamphlet, *Strena seu de nive sexangula*, "A new year gift of hexagonal snow"[7] he describes snow crystals as the result of the aggregation of water spheres of equal size which, interacting with each other, reach equilibrium, arranging themselves in regular hexagons. Studies

[4] V. Biringucci, *De la Pirotechnia*, a cura di Aldo Mieli, Società Tipografica Editrice Barese, Bari, **1914**, 198 p.

[5] Carobbi, Mineralogia 1. *I Fondamenti di Cristallografia e Ottica Cristallografica* by F. Mazzi and G.P. Bernardini USES, Firenze, **1983** 262 p.

[6] C. J. Schneer, *Eur. J. Mineral.* 1995, 7, 721-734.

[7] J. Kepler, *Strena seu de Nive Sexangula,* Frankfurt am Main, Gottfried Tampach, **1611**. English translation: C. Hardie with essays by B.G. Mason and L.L. Whyte, *The six-sided snowflakes*, Oxford University Press, Oxford, **1966**.

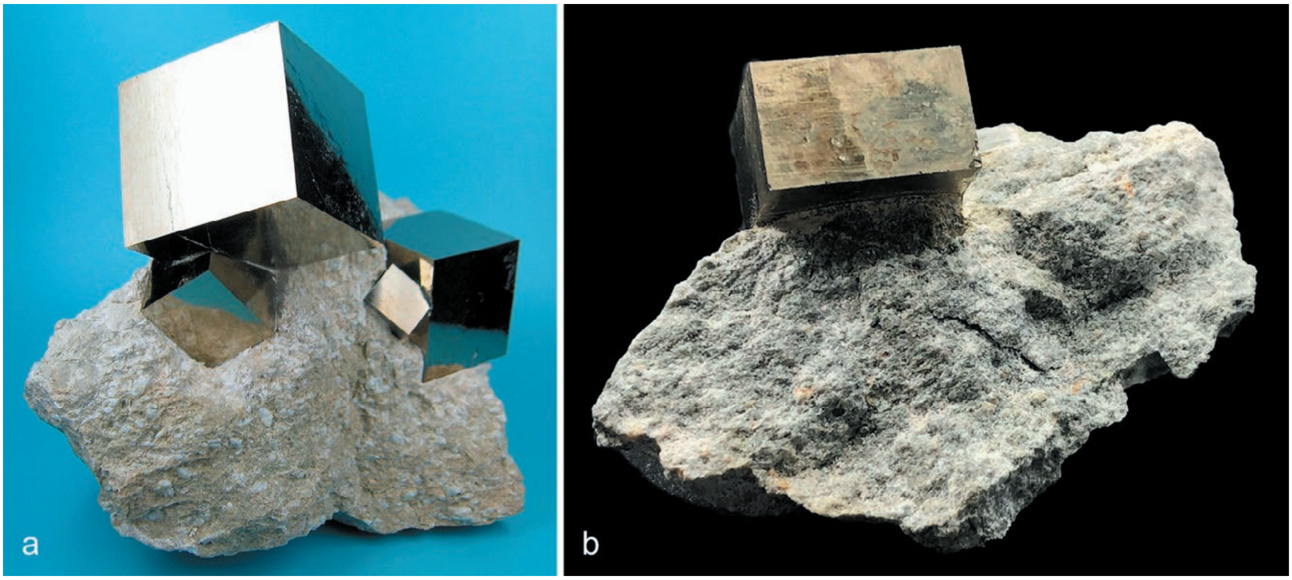

Fig. 3. Crystals of pyrite. 3a: Pyrite in geometrically regular cubes (https://en.wikipedia.org/wiki/Pyrite). 3b: "Cubes" of pyrite with rectangular faces (https://i.etsystatic.com/16351195/r/il/5994c7/1719730471/il_fullxfull.1719730471_rcxj.jpg).

Fig. 4. Portrait of Georgius Agricola (unknown painter, https://commons.wikimedia.org/w/index.php?curid=4858286).

of snowflakes led Kepler to formulate the idea of close packing of spheres. The so-called Kepler conjecture, only recently demonstrated[8], tells us that there is no way to arrange equal spheres in space with a density greater than that of the hexagonal close packing or the cubic close packing, with centered faces. According to Authier [3] (p. 372), Kepler's intuition is a milestone for the concept of the space lattice.

Robert Hooke (1635-1703), contributed to the emerging science of crystallography by developing pioneering models to deduce the distribution of the atoms' disposition in the structures from the shape of macroscopic crystals. For example, by variously combining identical spheres (close packing), he had managed to reproduce the external shape of alum octahedra (Fig. 5). According to Hooke[9], by combining the equilateral triangle (A) and the square (L) (Fig. 5), one can reconstruct the shape of vitriol, quartz, saltpeter etc. Authier [3] (p. 399) highlights that Hooke "had already implicitly observed the constancy of interfacial angles, noting the extension of crystal faces depended on the number of spheres added on each plane during the growth of the crystal."

Rasmus Bartholin (1625-1698 brother of Thomas, teacher of Steno) discovered a curious optical property

[8] T. Hales, M. Adams, G. Bauer and 19 others *A formal proof of the Kepler conjecture*, Forum of Mathematics, Pi, **2017**, 5, e2, 29 pp., doi: https://doi.org/10.1017/fmp.2017.1

[9] R. Hooke, *Micrographia*, Jo Martin, and Ja Allestry, printers to the Royal, Society, London, **1665**.

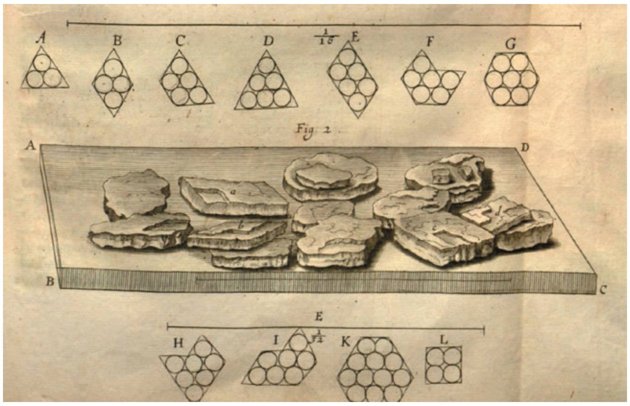

Fig. 5. Hooke's reconstruction of alum crystals by close packing of identical spheres. After Hooke, 1665 [9] (https://authors.library.caltech.edu/23510/1/BMC_Hooke%27s_Models.pdf).

shown by transparent calcite crystals of Helgustaðir ("Icelandic spar") from eastern Iceland. A black dot marked on a sheet is doubled in two points when viewed through the faces of a calcite rhombohedron. The phenomenon was later identified and took the name of double refraction.

Christiaan Huyghens (1629-1696) formulated the theory of the wave nature of light useful to explain reflection and refraction phenomena. The phenomenon of double refraction was also explained with Huyghens' theory. He also assumed that calcite was made up of particles in the form of flattened ellipsoids of rotation, with the rotation axis parallel to the ternary axis of the rhombohedron. In this way he explained the rhombohedral cleavage of calcite.

Finally, Domenico Guglielmini (1665-1710), a mathematician, chemist and physician lived shortly after Steno. He was one of the first to take an interest in salt crystallization. In particular, in his articles, there are important observations on the morphology of crystals such as saltpetre, vitriol, rock salt and alum synthesized in the laboratory. Very interesting is Guglielmini's observation on rock salt cubes: although the shape of the crystals may be faulty "the inclination of the sides is always stable, which does not vary by one point from the right angle, typical of the cubic figure" (quoted in P. Aloisi, p. 167). It cannot be denied that the constancy of the angles for rock salt is clearly delineated. Guglielmini also contributed in an interesting way to the knowledge of the structure of crystals. In a well documented article entitled "*Domenico Guglielmini e la Cristallografia*", the author (P. Aloisi[10]) analyzes Guglielmini's writings in relation to the results of Biringuccio, Steno, Hooke, Huygens, Romé de l'Isle and Haüy and concludes "... without wanting to diminish the great merits of Romé de l'Isle and Haüy, it can be said, it seems to me, that a century before them, and in more difficult conditions, Guglielmini had already laid the fundamentals of crystallography" (P. Aloisi [10], p. 175).

STENO

Steno arrived in Italy in 1666, preceded by his fame as a great expert in anatomy, but during the two-year stay in Tuscany he also turned his interest to geology, mineralogy and crystallography. The Grand Duke involved Steno in various problems such as dissections of fish and human corpses, study and cataloging of fossils and minerals, geological excursions, etc. At the end of the two-year period he hastily wrote the famous *Prodromus* (Fig. 6), which was edited by his friend Vincenzo Viviani and published in 1669.

NICOLAI STENONIS
DE SOLIDO
INTRA SOLIDVM NATVRALITER CONTENTO
DISSERTATIONIS PRODROMVS.
AD
SERENISSIMVM
FERDINANDVM II.
MAGNVM ETRVRIÆ DVCEM.

FLORENTIÆ
Ex Typographia sub signo STELLÆ MDCLXIX.
SVPERIORVM PERMISSV.

Fig. 6. Title page of Steno's Prodromus (Florentia: Ex typographiae sub signo Stellae, 1669).

[10] P. Aloisi, *Periodico di Mineralogia*, **1937**, 8, 163-175.

To conduct his research Steno could take advantage of the results previously achieved by e.g. Vannoccio Biringucci, Georgius Agricola, Johannes von Kepler, Robert Hooke, Christiaan Huyghens and Erasmus Bartholin but he also had to fight against a series of mythological beliefs, superstitions and dogmatic bonds. Particularly hard to believe, at least nowadays, the "*vis formativa*" for which fossils and minerals would form directly in the rocks by celestial influence ("principle" supported by e.g. Michele Mercati, 1541-1593) or the "*succus lapidescens*", petrifying juice that caused diamonds to reform in their fields a couple of years after they were removed ("principle" supported by e.g. Anselmo Boetius de Boot, 1550-1636). Michele Mercati and Anselmo Boetius de Boot were very influential, because they were the personal physician of the pope and of the emperor, respectively.

After a preamble of dedication to the Grand Duke and an illustration of the *Prodromus* content, Steno lists a series of almost dogmatic declarations. Only those most relevant to the present topic are reported here.

1. A natural body is made up of imperceptible particles accessible to the actions coming from magnet, fire and sometimes light; you can find free passages both between the particles and inside them (Stenone [2], p. 9). It seems very likely that Steno thought of particles juxtaposed to form a solid and was far from the intuition of a homogeneous-discontinuous-periodic sequence of atoms.

2. Distinction between fluid (moving particles) and solid: the particles never move away from each other "for as long as that solid remains solid and intact" (Stenone [2], p. 9). But "when a solid is formed, its particles move from one place to another" (Stenone [2], p. 9).

Steno was very interested in the problem of the movement of particles; in fact, he promised to analyze in detail the various causes of motion in the proposed Dissertation but which never was published. However, even in the *Prodromus* the exposition of the problem is very detailed and sometimes a little dispersive. After long discussions, which also acknowledge the existence of a divine force, he concludes that the movement of the particles in what is produced by Nature derives from the movement of a fluid that enters it. This fluid can come from the Sun or other source. (Stenone [2], p. 9-10).

Evidently Steno follows Descartes on the cosmic ether spread throughout the universe. As we know, this mysterious entity was thought to exist until the early twentieth century.

3. The sequential order of solid formation is defined (see the full title of the *Prodromus*). For example, fossils are formed before the rocks that contain them; mineralized veins are formed subsequent to the embedding rocks (Stenone [2], p. 12). This statement is based on Steno's principle of molding as explained by Kardel.[11]

4. Bodies with the same shape and intrinsic characteristics will be equal also as regards the place of formation (a somewhat risky statement, as observed by A. Mottana in Stenone [2] (p. *XI*), and the way they grow (Stenone [2], p. 13). Quartz and saltpeter are both formed by deposition from a fluid that is not necessarily aqueous (molten e.g. for quartz). In this regard it is worth mentioning a paper by F. Rodolico[12] relating to the "*Cristalli di quarzo descritti da Nicola Stenone*". Interesting observations by Steno are reported on the mixed inclusions present in the quartz crystals. Steno says that many inclusions are made up of only air and therefore quartz cannot have formed from a water fluid because otherwise all inclusions would be water and it is known "that the water thus contained cannot evaporate for any series of centuries" (Stenone [2], p. 26).

5. A natural body is always produced by a fluid (Stenone [2], p. 14); at present we know that this is not always true for some metamorphic minerals.

6. The growth of a solid occurs by juxtaposition of particles precipitated by an external fluid and not by "digestion from within" as in a vegetable (Stenone [2], p. 14) (see below).

This is a concept of great importance in Steno's scientific thought.

Crystal (Quartz) (Stenone [2], p. 25-30)

To continue our discussion of Steno's crystallographic approach, we should focus on the mineral quartz. Steno prefers the term crystal, used by Pliny, to quartz, adopted by Agricola. It was believed that the clear and transparent quartz crystals, common in the mountains, were formed by a sort of super cooling of "permanently hardened" water. Of course Steno is against this hypothesis, as can be seen from the sentence "On the basis of what has been exposed so far, it would be legitimate to demonstrate that extreme cold is not the *efficient cause* of crystal (quartz)" (Stenone [2], p. 30). Steno's use of the words, "efficient cause" is very interesting. As we know, Aristotle asks himself the following question: Why do things arise, grow and die? He identifies four categories of causes in this regard: material, formal, efficient (or moving cause of a change or movement), and final. It is

[11] Troels Kardel, "Prompters of Steno's geological principles: Generation of stones in living beings, glossopetrae and molding," in *The Revolution in Geology from the Renaissance to the Enlightenment* (Ed. G. D. Rosenberg), Geological Society of America, Memoir 203, **2009** Boulder, CO., pp. 127- 134.

[12] F. Rodolico, *Rivista Storia Scienze Mediche e Naurali,* **1955,** 1-6.

therefore evident that even in the 17th century, the Aristotelian categories were still influential.

According to Steno, crystal (quartz) is composed of two hexagonal pyramids, (we know that instead it is the combination of two rhombohedra, direct and inverse) and an equally hexagonal intermediate column that is the hexagonal prism. It is strange that a keen observer like Steno never mentions the little faces of the trapezohedron and of the trigonal bipyramid, which are very useful in distinguishing the right from the left quartz. Yet he must surely have seen them in the numerous quartz samples at his disposal.

After specifying the terms that he uses to describe the crystalline form, he goes on to explain the model of crystal growth that occurs by juxtaposing particles from an external fluid.

a) The crystal grows from an initial germ (on whose nature Steno declares himself incompetent) by juxtaposition of particles precipitated by an external fluid. Steno rejects growth by addition within the crystal as would be the case for growth of living things. (Stenone [2], p. 27). This "*vegetative*" principle recalls the ancient beliefs on mineral deposits whose arrangement was compared to that of the blood veins in the bodies of animals or to the branches of trees in the woods. Since a mineral deposit was thought to have formed inside a mountain, it was compared to a large branching tree with roots at the base of the mountain.

b) The particles are not distributed randomly on all planes (faces of the crystal) but, first on the apexes, then on the "pyramidal" faces, and then on the faces of the column (hexagonal prism). Therefore, the faces of the hexagonal prism (quadrilateral planes, constituted by the bases of the "pyramidal" faces) are sometimes large, sometimes small or completely missing (Fig. 7a and 7b). (Stenone [2], p. 27).

Furthermore, the quadrilateral planes are often striated for the same reason (Fig. 8).

c) The crystalline matter is superimposed on the various "pyramidal" faces at different times and in different quantities: therefore the "pyramid" axis does not always form the same straight line with the column axis (see Fig. 12, section 4). The faces of the "pyramids" are hardly equal to each other, and not always triangular (Stenone [2] 1995 p. 27) (Fig. 9) while the intermediate planes (faces of the hexagonal prism) are not always equal to each other and are not always quadrilateral. The solid angle of the vertex can be broken down into numerous solid angles so as to appear as an edge (Stenone [2], p. 27) (Fig. 9).

d) It may happen that the crystalline material does not spread evenly on the faces of the "pyramids" and the

Fig. 7. Crystals of quartz. 7a: Quartz with typical habit. 7b: Quartz with "bipiramidal" habit (https://www.mindat.org/photo-188888.html; https://www.mindat.org/photo-156304.html).

Fig. 8. Quartz crystal with striated faces (https://goldenhourminerals.com/listing/864704147/cristallo-naturale-colombiano-di-quarzo).

Fig. 9. Smoky quartz viewed perpendicular to the vertical axis (https://www.spiriferminerals.com/mini.php?id=2654&width=300&file=gfa30d.jpg).

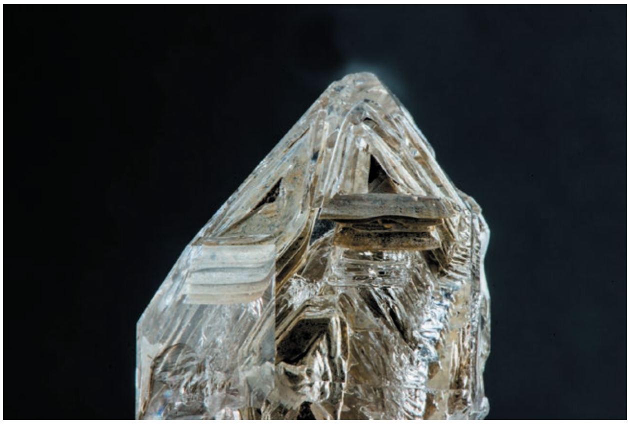

Fig. 10. Quartz: stepped crystal (https://sma.unibo.it/en/the-university-museum-network/mineralogical-collection-luigi-bombicci-museum/gallery/).

Fig. 11 Quartz: fracture surface (https://geology.com/minerals/quartz.shtml).

edges develop more than the faces (Stenone [2], 1995, p. 27-28) (stepped crystals, Fig 10).

e) The hardening occurs at different times so the faces may not be completely smoothed. A fracture surface is smoother than the crystal faces (Stenone [2] 1995 p. 28) (Fig. 11).

f) Why does crystalline matter settle at one point of the growing crystal rather than another?

Steno writes that this depends on the characteristics of the growing crystal and not on those of the nutrient fluid (Stenone [2], p. 28-29).

"Corpi angolati": Angular bodies

After quartz (crystal), Steno deals with other angular bodies, that is convex solids with interfacial angles; in particular hematite, diamond and pyrite.

With angular bodies of iron, he describes the various habits typical of hematite, namely rosettes (including micaceous hematite), "oligisto" with twelve faces and the crystals with 24 faces. Steno also investigates the way hematite is formed and grown in analogy to what was said for quartz. For diamond, in addition to the description of the various habits, he examines the analogies with the formation and growth of quartz and rejects the hypothesis that this mineral can re-form, in a few years, in the place from which it was extracted.

The marcasite (pyrite) that Steno deals with is always in cubes; it is likely that, as Mottana (in Stenone [2], p. *XV*) observes, it was not a pyrite from Elba which, at least today, is mainly in pentagonal dodecahedra. Steno describes the perfection of cubic crystals (although in general Steno defines them as rectangular parallelepipeds because rarely faces are all the same), and the "trigliph" striated faces for which he finds a very complicated explanation linked to the movement of the fluid. Even the relationships with the rocky matrix are described with complex mechanisms for which he also refers to the "Magnus" Galileo. The end result, however, leads him to erroneously conclude that pyrite was formed before the embedding rock.

Non mutatis angulis

In Fig. 12, the upper part of the only image included in the *Prodromus* is shown. The first seven drawings represent vertical sections of a quartz crystal. In particular, section 1 (with four sides: a rhombus) refers to a crystal with a "bipyramidal" habit in which the column, i.e. the hexagonal prism, is completely absent (see Fig. 7b). In sections 2 and 3 (with six sides) the faces of the hexagonal prism do appear: in section 2 less developed than in 3 (see Fig. 7a). In section 4 irregularities appear in the faces such as the axes of the parts that make up the body of the crystal do not form a straight line. Sections 5 and 6 show that in the plane of the axis both the number and the length of the sides can change, while not changing the angles. Steno defines this characteristic with the three words (*non mutatis angulis*) which have become very famous. At the same time, several cavities remain in the center of the crystal and various little layers are formed. Finally, section 7 shows, always in the plane of the axis, the variation in the number and length of the sides when the new crystalline matter overlaps the faces of the "pyramids". The growth takes place layer by layer.

Drawings 8 to 12 show similar variations, but seen in sections perpendicular to the vertical axis. We pass

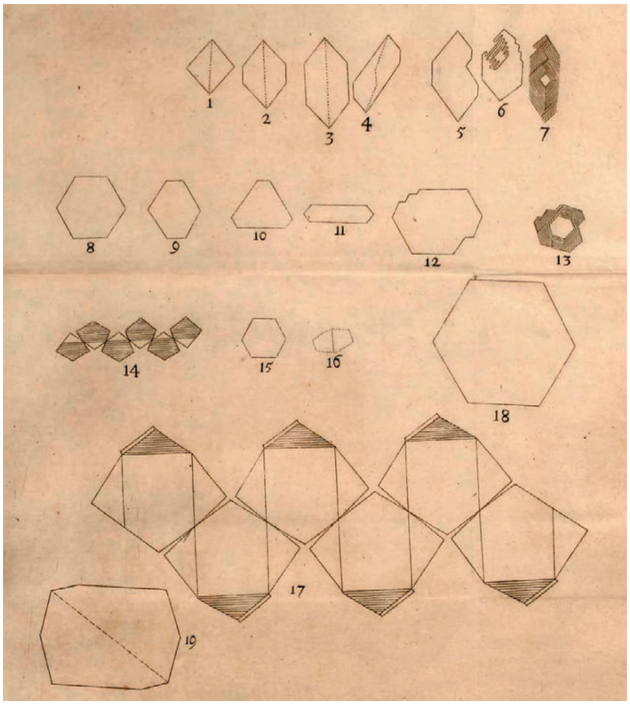

Fig. 12. Detail of plate published in Steno's *Prodromus.*

from a regular hexagon to figures with sides gradually different in length and then also in number.

Section 13 indicates how, when new matter is added on the face of the pyramids, sometime they change their length and the number of sides composing the base, but without changing the angles (*non mutatis angulis).*

The comparison between Steno's drawing and the result of modern X-ray investigations is impressive (Fig. 13).

Drawings 14 to 19 refer to the various types of hematite described in the text, and are a bit more complex. It should be noted that, for hematite, the sentence "non mutatis angulis" never appears.

As a curiosity we can add that Schneer[13] notes that some of Steno's drawings, from his only illustration (Fig. 12), are similar to those of Hooke and he wonders if Steno may have been influenced by having perhaps seen Hooke's *Micrographia* during his stay in Paris. Of course the question is unanswered.

CONCLUSIONS

As we have already said, Steno could rely for mineralogy, crystallography and in general for the Earth

Fig. 13. Growth steps in a plane of quartz when seen down the c-axis. Left: enlargement of Steno's sketch (Stenone [2]; see Fig. 12). Right: X-ray topographic image of quartz exhibiting the typical dislocations and bands due to crystal growth (modified after Authier, 2013 [3]).

Sciences on the results published before him by scientists of considerable stature. As claimed by Authier [3] (p. 400), Steno was very familiar with the works of Kepler, Descartes, Bartholin and almost certainly Hooke too. However, these authors are never mentioned, perhaps because the *Prodromus* is a hasty text; perhaps they would have been mentioned in the "*Dissertazione*", which was never published. For example, the two crystallographic-groundbreaking concepts expressed by Steno, *Non Mutatis Angulis* and *Crystal Growth* (in particular quartz), had certainly some precursors in Biringucci, Kepler and Hooke. Democritus (Stenone [2], 1995, p. 3), Seneca (Stenone [2], 1995, p. 8), Hippocrates (Stenone [2], 1995, p. 16), Descartes (Stenone [2], 1995, p. 20) and Galileo (Stenone [2] 1995, p. 34) are mainly cited for philosophical reasons except Galileo mentioned in the discussion on the formation of pyrite, but with the wrong conclusion (certainly not because of Galileo) that pyrite was formed before the embedding rock.

It should never be forgotten that, mythological legacies, deep-seated superstitions and dogmatic bonds were still widespread and could also lead enlightened researchers to conclusions with no scientific value. An exemplary character to understand this mentality is Michele Mercati, a great scholar of rocks, minerals and fossils who was responsible for the "*Vatican Metallotheca*", the most important naturalistic museum of the Renaissance. In an interesting and exhaustive article entitled "*Michele Mercati (1541-1593) e la Metallotheca*", Accordi[14] illustrates the theories of Mercati, basically a follower of Aristotle, who, in support of his theses, does not hesitate to report full passages of the Greek philosopher. Accordi[14] (p. 12) writes: "By treating minerals he, like almost all his predecessors, fully accepts the theory

[13] C. J. Schneer, in *Steno as geologist* (Ed. *G. Scherz*), Odense, University Press Copenhagen, *Acta Hist. Sci. Nat. Med*, **1971**, *23*, p. 293-307.

[14] B. Accordi, *Geologica Romana*, **1980,** *19*, pp. 1-50.

of their genesis by condensation with the force of heat, or cold, in the presence or absence of air with or without the help of fire; therefore little progress since the time of Albert Magno (13th century)."Another singular aspect concerns citations of previous works. Accordi explains why Mercati, who cites the numerous sources he consulted, even though he publishes three drawings of the great Conrad Gesner (1515-1565), never cites him, as if he had never existed. Gesner was officially forbidden to Mercati as "heretic": he was a Protestant. It is worth remembering that Steno had the opportunity to read Mercati's manuscript (on *Metallotheca*) with the permission of the Florentine scholar and scientist Carlo Dati who had found and purchased it in 1665[15].

Steno was usually able to eliminate these prejudices from his experimental way of inferring, but he was not always successful at eliminating them from the thoughts of others.

As suggested by Abbona[16] in his extensive essay "*Niccolò Stenone, un modello di ricercatore*", we can refer to Steno's manuscript entitled *Chaos* (discovered only in 1946) as an important source of news about his personality. Steno writes: "In matters of natural sciences it is good not to bind to any theory, but to classify observations in order by trying to arrive at some result on one's own initiative. In the field of natural sciences we derive our knowledge only from experiments and observations and from all that we can detect with metaphysical and mechanical principles." And he continues "because nothing is more difficult than putting aside prejudices, even modern works are not free from traces of preconceived ideas, and if I wanted to make an exception, I would deserve censorship for my brazen pride" (quoted in Abbona [16], p. 68).

It is probable that also for this reason his lively and pragmatic *Prodromus* has fallen into oblivion for a long time, despite an English translation and a second edition in Latin (shortly after the first Florentine edition) printed in Leiden, home of the most ancient University of the Netherlands where Steno had followed courses in medicine, astronomy and others subjects.

However, there is no doubt that the *Prodromus* contains very remarkable observations also with regard to mineralogy and crystallography.

"*Non mutatis angulis*": as we have seen previously, these three words appear in the *Explicatio figurarum* about drawings 5 and 6 (longitudinal sections of quartz crystals). The same happens for drawing 13, the cross sectional drawing of a quartz crystal. Steno speaks about the number and length of the sides, but it is clear that, being in section, it is about the number and extent of the faces and the non-changing angles are interfacial angles. Therefore for quartz the constancy of the dihedral angles is clearly established. A current formulation (derived from Carobbi's *Mineralogy* [5], p. 5) of the general law expressed by Romé de l'Isle in 1783 is the following: at the same temperature, crystals of the same crystalline substance, (however and wherever they are formed, if with a morphology similar) exhibit faces, determining in pairs (in all crystals) equal interfacial angles.

The three words of Steno (*non mutatis angulis*) have had, especially in the past, a very strong following; but can it be assumed that it is really a true anticipation of the first law of crystallography such as to attribute its authorship to Steno? According to Aloisi [10] (p. 165), this is not the case. "The observation is confined to the explanation of the table; in the text there is no mention of the thing and for the other minerals (oligisto, pyrite, diamond) both in the text and in the explanation of the figures, absolute silence in this regard".

It is interesting to compare Aloisi's opinion with that of Authier [3] (p. 399-400): "This is the only place where Steno clearly states the constancy of interfacial angles. He presents it as a fact of observation, without proof, and not as an universal law and he refrains from relating it to any atomistic hypothesis about the inner structure of the crystal."

Pedersen[17] believes that this is essentially a philosophical problem; Steno limits himself to describing the constancy of the interfacial angles in quartz and implicitly in hematite. Pedersen continues (p. 123) "But it seems to be undeniable that Steno was the first scientist who put this insight to fruitful use even if he did not put it into relief as a fundamental law."

In conclusion, Biringucci, Libavius, Huygens, Hooke and others have expressed, for a single mineral, some ideas that, sometimes implicitly, lead to the concept of the constancy of the interfacial angles. Guglielmini represents a particular case as he deals with artificial salts; however his observations lead explicitly to the concept of the constancy of the angles at least for sodium chloride. Finally Steno's observations for quartz are precise and incontrovertible.

However, these are entirely confined to quartz and do not even extend explicitly to the other angular bodies (oligisto, pyrite, diamond) that Steno deals with. It therefore seems inappropriate to me to consider it a true anticipation of the universal law formulated by Romé de l'Isle.

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[15] E. Andretta, *Michele Mercati,* Dizionario Biografico degli Italiani, **2009**, *73*.

[16] F. Abbona, *Emmeciquadro* **2004,** *21*, pp. 65-86.

[17] O. Pedersen, *Stenoniana nova series Copenhagen*, **1991,** *1*, pp. 113-134.

"Crystal growth": his is truly Steno's most important intuition. The crystal grows from an initial germ (on whose nature Steno declares himself incompetent) by juxtaposition of particles precipitated by an external fluid. The growth takes place layer by layer; the growth speed is not the same for all faces; and the edges can grow faster than the faces. Crystalline matter is deposited in one point of the crystal instead of another due to the characteristics of the growing crystal and not those of the nutrient fluid.

As Dino Aquilano[18] writes (2014, p. 3): "It is therefore to this Danish genius, naturalist, geologist and anatomist ....., that we owe the concept of anisotropy of the solid state, which distinguishes crystals from any other state of aggregation of matter."

Steno was also honoured with a mineral species dedicated after him in 1962. *Stenonite* is a rare alumino-fluoride carbonate, $Sr_2Al(CO_3)F_5$, found and described by Pauly[19] at the Ivigtut cryolite locality Greenland. The crystal structure of stenonite has been solved and published by Hawthorne[20] in 1984.

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[19] H. Pauly, *Medd. Grønland*, **1962**, *169(9)*, pp. 1-24
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Steno and the Rock Cycle

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Abstract. Geologists categorize the basic types of rock according to their origin – igneous, sedimentary, or metamorphic – rather than by their physical properties. This is expressed dynamically by the fundamental concept of the rock cycle, which describes how the basic rock types are derived from one another within the Earth system as a result of ongoing cyclic geologic processes. In Nicolaus Steno's published geological work, particularly *De Solido,* he takes a similar approach, outlining how a substance can be examined "to disclose the place and manner of its production". Steno also recognizes the roles of erosion, transport, and deposition in the production of sedimentary strata from pre-existing Earth materials. His description and diagrams of the geological evolution of Tuscany also show a clear cyclicity of process. While the modern concept of the rock cycle did not emerge until the 19th century, Steno's work contains key elements of this important concept.

Keywords: Geology, rock cycle, rock classification, Earth processes, Nicolaus Steno.

INTRODUCTION

In his short scientific career, Nicolaus Steno produced two major works on geology. The first was an addendum to a 1667 report, *Canis Carchariae dissectum caput*[1], on the dissection of a shark head that he performed in Florence for the court of Grand Duke Ferdinand II. In the addendum Steno argued for the organic origin of fossil shark's teeth and other marine fossils (a contentious issue at the time) and for the sedimentary origin of the enclosing rock. He followed *Canis* two years later with a more expansive work, *De solido intra solidum naturaliter content dissertationis prodromus*[2], which was intended to be an abstract, or prodromus, for a much longer and more detailed study, but this full version never appeared.

Both *Canis* and *De Solido* include many acute observations on minerals, rocks, and fossils, but *De Solido* in particular is widely regarded as one of

[1] N. Steno, *Canis Carchariae dissectum caput in* Steno, N. Elementorum Myologiae Specimen: Florence, Stella, **1667**, p. 90-110. (English translation *in* Steno Geological Papers (Ed: G. Scherz) Copenhagen, Odense University Press, **1969**, pp. 66-131.

[2] N. Steno, *De solido intra solidum naturaliter content dissertationis prodromus*, Florence, Stella, **1669**, 78p. English translation *in* Steno Geological Papers (Ed: G. Scherz) Copenhagen, Odense University Press, **1969**, pp. 134-234.

the founding documents of the science of geology. It is best known for what geologists today refer to as his principles of crystallography and stratigraphy. Both are staples of introductory geology classes and reflect the view shared by Steno and modern geologists that mineral crystals and the Earth as a whole are not static objects, but dynamic entities with a history of growth and development. In fact, his stratigraphic principles of superposition, original horizontality, and lateral continuity laid the logical foundation for historical geology and the exploration of deep time.

My purpose here is to explore how another key concept in modern geology also appears in *De Solido*, albeit in a rudimentary form. This is the so-called rock cycle, which describes how the materials of the Earth's crust are continuously being created, destroyed, transformed, and recycled by geologic processes operating within the Earth and on its surface. Some elements of this idea have a long history, extending back as far as classical times, and it did not fully take shape until the 19th century with the work of Lyell and his contemporaries, so I make no claim here that Steno should be seen as the author of the rock cycle concept. Rather, this is an attempt to discern what elements of this important geological concept are present, and what are missing, in Steno's work, and the extent to which his conception of Earth processes can be considered a coherent rock cycle.

THE ROCK CYCLE

The cyclic view of Earth processes described by the rock cycle has deep historical roots. Aristotle and other classical writers observed marine fossils on land and in the rocks of mountains and proposed that there was a periodic interchange of land and sea[3]. The idea of cycles in Earth's history appears in the writings of Medieval writers in Europe and the Islamic world, as well as Renaissance thinkers such as Dante Alighieri, and Leonardo da Vinci[4]. Cyclicity was also a feature of several 17th and 18th century theories of the Earth[5]. These early "rock cycles" were primarily sedimentary. That is, they mostly considered cycles of erosion and deposition of sediment. Hutton is generally credited for giving igneous activity a significant role in his version of the cycle[6]. Metamorphism was later introduced by Lyell in his *Principles of Geology* 1833.[7]

Figure 1 shows a simplified diagram of the rock cycle, as generally conceived today. The main points of reference are three basic classes of rock: igneous, sedimentary, and metamorphic. Each type of rock represents not just the material itself but the geological context and processes that produced it. Igneous rock forms as magma or lava cools and solidifies. Igneous rock formed from magma that solidifies in the Earth's interior is plutonic rock. Igneous rock formed from lava that solidifies on the Earth's surface after an eruption is called volcanic rock. Sedimentary rock forms from the raw material of its source rock, which undergoes weathering, transportation, deposition, and ultimately lithification. Metamorphic rock forms as pre-existing rock – igneous, sedimentary, or other metamorphic – in the Earth's interior is altered by heat and extreme pressure to create altered rock with new mineralogy and/or texture.

As will be discussed in more detail below, the modern rock cycle is far more complex than what Steno could have imagined in 1669. Accordingly, the following discussion will focus on three underlying aspects of the cycle that are implicit in Steno's work: 1) the classification of rock by its mode of origin (generative classification), 2) derivation of rock from pre-existing Earth materials, and 3) cyclicity of Earth processes.

STENO AND GENERATIVE CLASSIFICATION

Classifying materials by their history or origin is a hallmark of geologic thought and has been called "generative classification" by Hansen.[8] It is different from the approach generally taken by ahistorical physical sciences such as chemistry or physics. A crystal of silicon dioxide (quartz) is silicon dioxide regardless of how, when, or where it formed, but geologists distinguish between a quartzose sandstone (sedimentary rock) and quartzite (metamorphic rock), even though their chemical makeup may be precisely the same.

Steno makes no attempt in *De Solido* to construct any system for describing or classifying rock, but he lays the foundation for the generative classification approach at the beginning of his *De Solido* as he lays out the general problem he aims to address:

[3] A. Cutler, *The Seashell on the Mountaintop*, Dutton, New York **2003,** pp. 8-9.; D. Oldroyd, *Thinking About the Earth: A History of Ideas in Geology*, Harvard, Cambridge, **1996**, pp. 7-28

[4] Pp. 24, 27 in Ref. 3, (Oldroyd).

[5] See S.J. Gould, *Time's Arrow, Time's Cycle*, Harvard University, Cambridge, **1987**, pp. 21-59 and F. Ellenberger, *History of Geology,* V. 2, Balkema, Rotterdam, **1999**, pp. 209-231 for examples.

[6] J. Hutton, *Theory of the Earth with Proofs and Illustrations,* William Creech, Edinburgh, **1795**. See ref 5 (Gould) for discussion Of Hutton's cycle.

[7] C. Lyell, *Principles of Geology*, V. 3, facsimile of first edition (1833), University of Chicago Press, **1991**, pp. 374-379.

[8] J.M. Hansen, On the Origin of Natural History: Steno's Modern, but forgotten philosophy of science, in *The Revolution in Geology from the Renaissance to the Enlightenment* (Ed: G.D. Rosenberg) Geological Society of America Memoir 23, Boulder, **2009**, pp. 159-178.

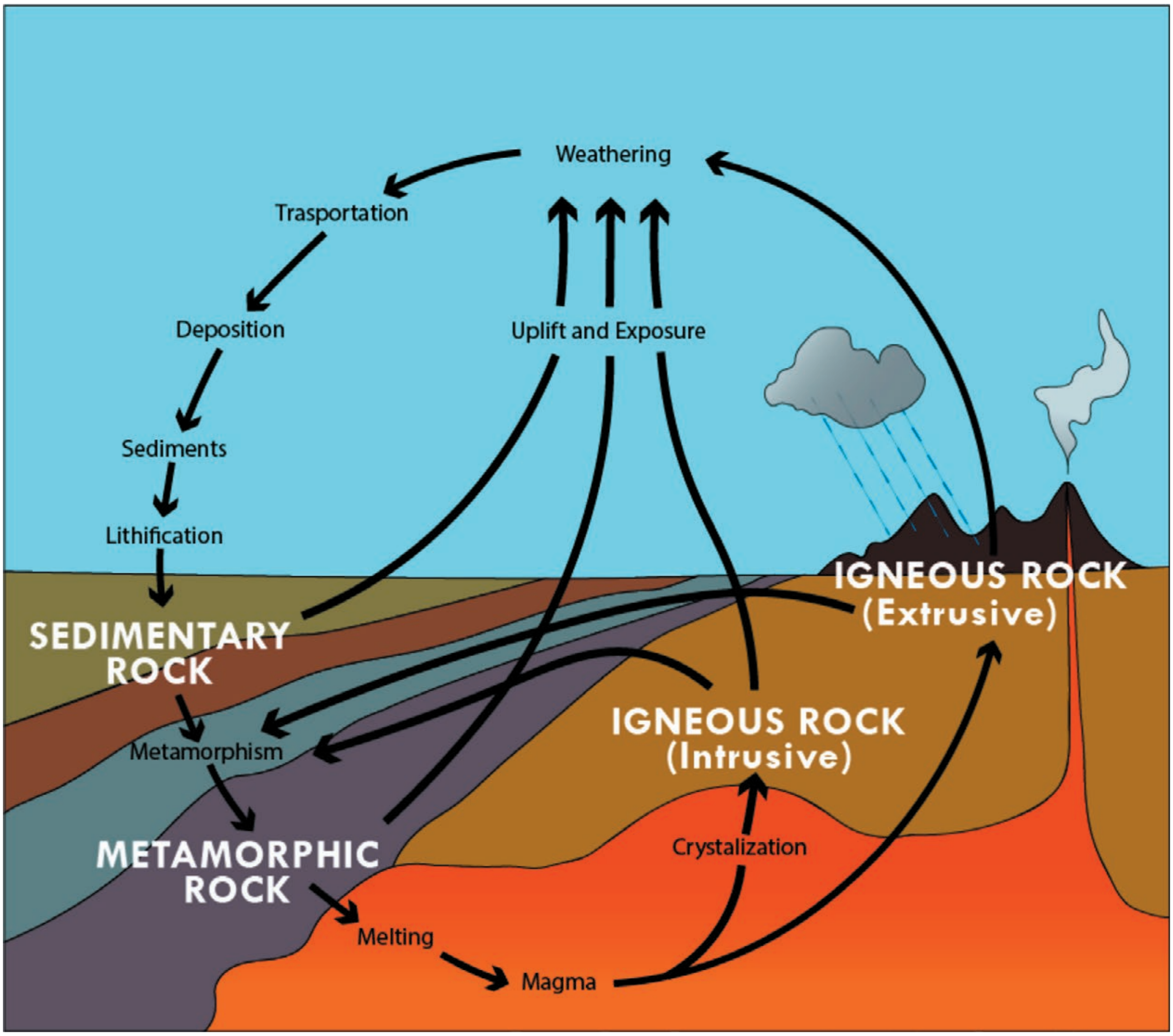

Figure 1. Typical depiction of the rock cycle. Arrows indicate processes and stages in the cycling between igneous, sedimentary, and metamorphic rock. See text for further explanation. Adapted from several sources by the author.

Given a substance endowed with a certain shape, and produced according to the laws of nature, to find in the substance itself clues disclosing the place and manner of its production.[9]

Gould[10] argued that one of Steno's most momentous insights in *De Solido* was his decision, as Gould put it, "to arrange solids within solids according to the causes that fashioned them". Gould saw Steno's "great taxonomic insight" as the key to the long-standing puzzle of fossils: were they the true remains of ancient organisms or merely simulacra created by vegetative forces within the Earth? Steno recognized that organic and inorganic bodies in rock necessarily differed in their place and manner of production. To discern the different origins of solids, Steno offered two propositions:

> *I. If a solid body is enclosed on all sides by another solid body, the first of the two to harden was that one which, when both touch, transferred its own surface characteristics to the surface of the other.*[11]

[9] P. 141 in Ref 2 (Scherz). Steno's reasoning here applies a method now termed "abduction", in which the most likely explanation is sought for a given set of observations. See J.E.H.Smith, Thinking from Traces: Nicolas Steno's Palaeontology and the Method of Science, in *Steno and the Philosophers* (Eds.: R. Andrault, R., M. Lærke M.), Brill, Leiden, 2018, pp. 177-200.

[10] S.J. Gould, *Hen's Teeth and Horses Toes*, Norton, New York, **1984**, pp. 69-78.

[11] P. 151 in Ref 2 (Scherz)

and

II. If a solid body resembles another solid body in all respects, not only in the state of its surface but also in the internal arrangement of the parts and particles, it will resemble it also in the method and place of production.[12]

The first is often referred to as the Principle of Molding[13] and the second as the Principle of Sufficient Similarity[14] or the Recognition Criterion.[15]

For organic bodies such as mollusk shells, their place of production was outside of the rock matrix that entombed them, or within the matrix, but while it was still soft and unlithified. Because their growth was unimpeded by a solid matrix, they invariably showed their characteristic shapes and ornaments without regard to the enclosing material. For inorganic bodies such as mineral crystals and metallic ore deposits, their place of production was *within* the solid rock matrix, or within fractures and voids within the rock. Growing *in situ*, their shapes were often constrained by the space available, and so did not show the same consistency as organic bodies.[16]

As for manner of production, Steno added a third proposition:

III. If a solid body was produced according to the laws of nature, it was produced from a fluid.[17]

Steno applied this principle to distinguish organic fossils from inorganic mineral growths,[18] but he applied it with even more force to rocks and rock strata. In *Canis* he discusses the aqueous origin of sedimentary deposits at length.[19] In *De Solido*, Steno follows his proposition of the Principle of Sufficient Similarity with this declaration:

The strata of the earth agree, in location and manner of production, with those strata that are deposited from turbid water.[20]

[12] P. 151 in Ref 2 (Scherz)
[13] Ref 5 (Gould)
[14] Ref 5 (Gould)
[15] Ref 3 (Hansen)
[16] Pp. 111-113 in Ref 1 (Scherz)
[17] P. 153 in Ref 2 (Scherz)
[18] In *De Solido* he argued that organic solids such as mollusk shells grow by addition of material from *internal* fluids delivered to growing surfaces through pores. In contrast, mineral crystals and other inorganic substances grow by addition of material to their external surfaces from *external* fluids. Steno rejects the idea that crystals grow "vegetatively," as others had speculated.
[19] Pp. 99-109 in Ref 1 (Scherz)
[20] P. 151 in Ref 2 (Scherz)

This relates, of course, to the origin of sedimentary rock, which is the type of rock Steno primarily observed in Tuscany and is the type that most commonly contains fossils. In both *Canis* and *De Solido* he describes graded bedding, the arrangement of sedimentary grains resulting from rapid settling from turbid water, in which larger particles (the first to settle out) are overlain by increasingly fine particles (which settle out more slowly). His description in *Canis* of the depositional process is particularly lucid:

If we believe that the water under discussion could receive muddy water, either from the ocean or from torrents, it is certain that the bodies which make the water muddy ought to sink to the bottom when the violent motion ceases. Nor do we need to seek diligently for examples of this type, since both the beds of rivers and their estuaries give sure proof of it. One thing should be noted here, – the bodies that make the water muddy are not all the same weight; thus it follows that, as the water gradually calms down, first the heavier particles then the less heavy ones settle out; the lightest particles, however, float longer in the vicinity of the bottom before becoming attached to it. It is clear, in consequence, that frequently different layers will be found in the same sediment.[21]

He also mentions it in *De Solido:*

The larger bodies constrained in these same strata obey for the most part the laws of gravity, not only with respect to the position of any individual body but also the relative positions of different bodies to each other.[22]

Steno also applies the Principle of Sufficient Similarity to sedimentary rock strata in recognizing "place" of production in the sense of sedimentary environment. A marine environment would be indicated by "traces of sea salt, the remains of marine animals, timbers of ships and substances similar to the sea bed".[23] On the other hand, strata containing terrestrial bodies such as pine cones and tree branches would have been laid down by "a river in flood or by a torrential outbreak", that is, in a fluvial environment.[24]

Steno recognizes another aspect of the place of production, that is, whether a sedimentary particle con-

[21] P. 105 in Ref 1 (Scherz)
[22] P. 161 in Ref 2 (Scherz). Geologists frequently use graded bedding within sedimentary rock strata to interpret tectonically tilted and overturned rock units, as it indicates the original "up" direction in contorted beds. Given Steno's invocation of gravity, it is possible that his observations of graded bedding in Tuscan strata were instrumental in his formulation of the stratigraphic principle of original horizontality. Any graded bedding he observed in inclined strata would have required him to mentally rotate the strata to a horizontal orientation.
[23] P. 163 in Ref 2 (Scherz)
[24] P. 163 in Ref 2 (Scherz)

tained within sedimentary rock was produced elsewhere and transported to the site of deposition or produced *in situ* (allochthonous or autochthonous, respectively, in modern terminology).

> *Sediments are then formed when the contents of a fluid sink under their own weight regardless of whether these contents have been conveyed there from elsewhere or have been secreted gradually from particles of the fluid itself, either in its upper surface or from all the particles of fluid".*[25]

In effect, Steno appears to recognize the distinction between detrital and chemical sediments. He further notes that autochthonous chemically deposited bodies can be eroded and deposited elsewhere as allochthonous detrital grains. Referring to agates, he writes "incrustations of this kind are often found away from the place of production because the material of the place has been scattered by the bursting of the strata",[26] the abraded surfaces of these clasts in deposits being the clue to their allochthonous origin.

The Principle of Molding is applied by modern geologists when determining the allochthony or autochthony of sedimentary grains. Allochthonous mineral grains, such as sand grains or pebbles and other larger clasts in detrital rocks, are solid before deposition, so they commonly retain their original shape and do not interlock as the sediment is compacted and lithified. But autochthonous cement minerals that form *in situ* after deposition during lithification fill in the pore spaces between the allochthonous grains, creating an interlocking crystalline mass that binds the rock together and conforms to the shape of the pre-existing grains. This clastic texture in detrital sedimentary rock, with allochthonous clasts bound together by autochthonous cement, is distinct from the crystalline texture of chemical sedimentary rock such as rock salt or igneous rock such as granite, in which the mineral crystals are dominantly autochthonous and intergrow with one another as the minerals either precipitate from aqueous solution or crystallize from cooling magma. The Principle of Molding applies here as well: later-growing crystals fill in the spaces between earlier-growing crystals and take their shape from these spaces, allowing the sequence of crystal growth to be determined.

Geologists apply all three of Steno's principles in describing and classifying rock according to its origin, but nearly missing from Steno's discussion is rock that could be described as metamorphic or igneous. The absence of metamorphic rock from Steno's geology is not surprising; it was not recognized as a distinct form of rock until the 19th century. Further, metamorphic rock does not form from a fluid, the transformations that create it occur in the solid state. But igneous rock does form from a fluid – magma. Though Steno makes a brief allusion to volcanoes in his discussion of the origin of mountains, where he writes that mountains can form from "the eruption of fires that belch forth ashes and stones together with sulphur and bitumen"[27], nowhere does he mention rock or any solids forming from molten fluids. This is somewhat surprising, given that as a goldsmith's son he would have been familiar with molten metals. He was certainly aware of writing on volcanoes by Kircher and others, and he traveled to Elba where he would have had the opportunity to observe granite in outcrop. We can only speculate whether his planned dissertation to follow up *De Solido* would have included a discussion of igneous rock.

DERIVATION OF ROCK FROM PRE-EXISTING MATERIALS

According to the rock cycle, all rock in the Earth's crust is derived from pre-existing materials which have a history that extends backward in time to the formation of the Earth. This is an idea implicit in much of *De Solido*, where Steno discusses the origins of detrital sedimentary rock and attempts in its last section to lay out a geological history of Tuscany, going back to the primordial strata at the time of Creation. He makes it explicit in a later sermon:

> *This holds for diamonds and all precious stones whose matter certainly was created at the beginning of time with the other material of the universe, and was mixed with the other particles of solid and fluid bodies until, after the destruction of the earth it was secreted in old subterranean caves and took shape now to be used by human toil to be used for its own purposes.*[28]

In the sermon, Steno's intention is not scientific, but theological – he attributes minerals "not created by God, but after the malediction of earth" to the curse on Adam after the Fall.[29] The concept of a history of recycling behind geological materials is clear enough, however.

In *De Solido* Steno describes a fossil shell he recognized as having been reworked from a deposit older than the deposit where it was found:

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[25] P. 161 in Ref 2 (Scherz)
[26] P. 161 in Ref 2 (Scherz)
[27] P. 167 in Ref 2 (Scherz)
[28] Steno, N. "Ornaments, Monuments, Signs, Arguments" *in* Steno Geological Papers (Ed: G. Scherz) Copenhagen, Odense University Press, **1969**, p. 251.
[29] P. 251 in Ref 23 (Scherz)

A shell, partly destroyed internally, in which a marble incrustation, covered by various balanoids, had replaced the substance eaten away; thus it is possible to conclude with certainty that the shell had been left upon the land by the sea, then carried down to the sea, covered again by a new deposit and abandoned by the sea.[30]

He bases this conclusion on his taphonomic observations that the shell had diagenetic features (the marble encrustation, which implied previous burial and lithification) that were overlain by marine barnacles (balanoids), implying a second exposure in a marine environment before ultimate burial in the sedimentary stratum in which it was found.

Not only are fossils recycled and preserved, but rock particles can be as well. Steno notes that "fragments of another stratum" can be found in a stratum, making it "certain that the said stratum must not be counted among the strata that settled out of the first fluid at the time of Creation".

CYCLICITY OF EARTH PROCESSES

Two aspects of the cyclicity of Earth processes as described in the modern rock cycle deserve mention. The first is that the rock cycle has no set time frame. That is, the stages or transitions described in the cycle can occur over time scales ranging from very short (days, or even less) to very long (billions of years). Erupted volcanic ash can become "sediment" virtually instantly upon eruption, whereas plutonic igneous rock can remain uneroded and unmetamorphosed for billions of years. This lack of a regular time frame distinguishes it from many familiar cycles in science, such as astronomical and seasonal biological cycles. More to the point for the discussion here, though, is that this lack of a set time frame distinguishes the question of the cyclicity of Earth processes from the question of the cyclicity of time itself. The conflict between cyclic models of time (as conceived by Aristotle, for example) and linear models of time (as laid out in the Bible) has been discussed a length elsewhere.[31] While a cyclic model of time necessarily implies a cyclicity of processes, linear models of time can also easily accommodate subordinate cyclicity. For this reason, Steno's religious faith and commitment to the Biblical narrative of Creation would have posed no necessary impediment to his acceptance of cyclic processes.

[30] Pp. 195-197 in Ref 2 (Scherz)

[31] S. Toulmin and J. Goodfield, *The Discovery of Time*, University of Chicago, Chicago, **1982**, 280 p.; S.J. Gould, *Time's Arrow, Time's Cycle*, Harvard University, Cambridge, **1987**, 222 p.; and many others.

A second aspect of the rock cycle is that it does not necessarily follow the set sequence shown by the outer circle of arrows in the Figure 1. Igneous rock is not inevitably eroded to create sediments and sedimentary rock, sedimentary rock is not inevitably altered to become metamorphic rock, and, finally, metamorphic rock is not inevitably melted to create magma and igneous rock. As the arrows passing through the circle illustrate, rock of any type at any stage of the cycle can be uplifted and weathered to produce sediments, and igneous rock can be altered to become metamorphic rock without any intermediate conversion to sediment or sedimentary rock. Finally, though not shown on the diagram, igneous rock can be re-melted to create magma which then crystallizes into new igneous rock, and, similarly, metamorphic rock can be "re-metamorphosed" by changing conditions to make new metamorphic rock.

As discussed above, Steno makes no mention of the igneous and metamorphic elements of the rock cycle, aside from some passing references to fire and heat. For this reason, the kinds of transformations and cycles-within-cycles possible within the modern cycle do not appear in Steno's version of the cycle. It is essentially a sedimentary rock cycle.

The part of the sedimentary rock cycle that Steno devotes most of his attention to in *De Solido* is sedimentation, including the formation of graded bedding, as discussed above. Oddly, despite his emphasis on the hardening of sediments into rock in his Principle of Molding, Steno offers no account of lithification, besides a few scattered hints. In *Canis* he describes precipitation of dissolved bodies from transparent liquids to produce solids and observes that lime and gypsum can bind together fossil shells.[32] In *De Solido*, following his proposition that all solids are produced from fluids, he discusses at length the growth of mineral crystals, incrustations and organic tissues but makes no clear reference to either the compaction of sediments or the cementation of sedimentary grains.

The next stage of the rock cycle, in which rock buried within the crust becomes exposed to surface weathering and erosion, gets more attention from Steno**.** This stage happens either by uplift, raising marine strata above sea level, for example, or by a drop in sea level, exposing the former sea bottom to subaerial weathering and erosion. Either way, whether it is the land that rises or the water level that drops, this is a key step in the rock cycle. It makes the rock available to become broken down to become sediment and ultimately new sedimentary rock. Steno describes both uplift and sea level change in *De Solido*.

[32] Pp. 105-109; p. 97 in Ref 1 (Scherz)

Steno states that "mountain peaks can be raised and lowered"[33], attributing their formation mainly to the "alteration in the position of strata".[34] How does this happen? Steno proposes two mechanisms:

The first way is the violent upheaval of strata, whether this be due mainly to a sudden flare of subterranean gases or to a violent explosion of air caused by other great subsidences nearby. This upward thrust of strata is followed by the dispersal of earthy material as dust and the shattering of rock material into pebbles and rough fragments.[35]

and

The second way is a spontaneous slipping or subsidence of the upper strata after they have begun to crack because of the withdrawal of the underlying substance of foundation; in consequence the broken strata take up different positions according to the variety of cavities and cracks.[36]

In his second mechanism, the relative uplift and tilting of rock strata can be the result of collapse of cavities within the Earth[37]. This would not in itself raise the overall elevation of the rock strata, but it would create a more irregular land surface, with local highs creating mountains. Steno suggests that progressive internal collapse over time has made land surface more irregular:

It is completely uncertain what the depth of the valleys was at the beginning of the deluge; but reason persuades us that, in the first centuries of the world's existence, cavities were gnawn [sic] out by water and by fire, so that slight collapse of strata followed from this; however, the highest mountains, of which Scripture mentions, were the highest mountains then found, not the highest of those observed in the present day.[38]

As for sea level fall, the collapse of caverns described above could also open passageways into the Earth for surface water to drain, thus lowering sea level. This is the hypothesis Steno favors.

Who has investigated the structure of the interior of the earth and will dare deny the possible existence of huge spaces there, at times filled with aqueous fluid, at other times filled with aerial fluid? [39]

As for a subsequent rise in sea level that precedes the next cycle of sedimentation, Steno's mechanism is more complex. He proposes that volumes of water in the Earth's subterranean chambers could be heated by internal fires, causing it to be expelled to the atmosphere and fall as rain, which would then presumably cause the oceans to overflow onto the land. He also suggests that the bottom of the sea could be "raised up by the expansion of subterranean caverns."[40] This may be reference to the hypothesis of the Greek Geographer Strabo, who in an effort to explain marine shells found on land suggested that periodic upward flexing of the sea floor could displace ocean water and thus raise sea level.[41]

Rock strata uplifted and exposed, by whatever mechanism, are then weathered to produce sediment, which is eroded and transported to its site of deposition. The first step, the slow breakdown of rock by weathering, is not directly addressed by Steno. In *De Solido*, he attributes the "dispersal of earthy material as dust and the shattering of rock into pebbles and rough fragments" to the "violent upheaval" and "upward thrust" of rock strata.[42]

Sediment transportation is described by Steno in *De Solido* in several passages, emphasizing the "great quantity of earth" carried to the sea every year by rivers and "innumerable torrents.[43] Steno sees this as an ongoing process, with new sediment "added daily" to coastal deposits. This completes Steno's cycle, with these deposits potentially forming new rock strata.

CYCLES IN THE GEOLOGICAL EVOLUTION OF TUSCANY

Figure 2 shows Steno's conception of the geological evolution of Tuscany, which represents two cycles of sedimentation in six "aspects". Two aspects (22 and 25) represent marine deposition, two (21 and 24) represent the hollowing out of subterranean caverns (perhaps associated with the draining away of surface waters and the drop in sea level), and two (20 and 23) represent the collapse and shifting of strata to produce an uneven landscape.

Steno describes the first episode of deposition (25 in Figure 2) as occurring when "everything was cov-

[33] P. 169 in Ref 2 (Scherz)
[34] P. 167 in Ref 2 (Scherz)
[35] P. 165-167 in Ref 2 (Scherz)
[36] P. 167 in Ref 2 (Scherz)
[37] Descartes also invoked crustal collapse as mechanism for producing relief on the Earth's surface in his *Principia Philosophiae,* Amsterdam. Apud Ludovicum Elzerverium, **1644**. See Ref 3 pp. 45-47 (Oldroyd) for a description of Descartes' model.
[38] P. 207 in Ref 2 (Scherz). Steno illustrates these inferred caverns *De Solido* in his depiction of the evolution of Tuscany (21 and 24 in Figure 2), discussed below.
[39] P.207 in Ref 2 (Scherz)
[40] P.209 in Ref 2 (Scherz)
[41] F. Ellenberger, *History of Geology, V1*, Balkema, Rotterdam, **1996**, p.22
[42] P.165-167 in Ref2 (Scherz)
[43] P.209-211 in Ref 2 (Scherz)

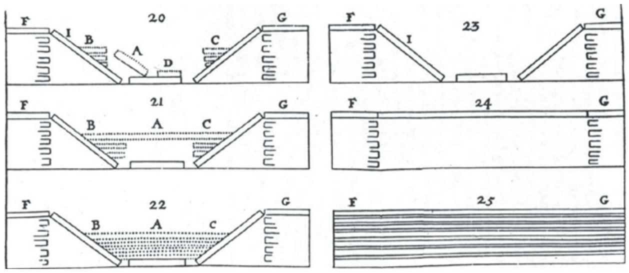

Figure 2. Steno's diagram of the geologic history of Tuscany in *De Solido*, showing two cycles of sedimentation and mountain-building. Time sequence goes from lower right (25) to upper left (20) in reverse numeric sequence. From Reference 2 (Steno).

ered by water"[44], as described in Genesis. These strata were deposited by the first fluid "devoid of plants, animals, and other solids." He does allow the possibility that younger strata containing "various bodies" might in some places lie unconformably above the primal strata laid down by the first fluid, but these younger strata are not shown in the diagram. Also not shown in the diagram is any indication of a source for the sediments in these original strata. In a time when the entire world was covered by water, there would have been no exposed land to supply detrital sediments. It may be that Steno conceived these sediments as being chemical sediments derived from materials dissolved in the first fluid at Creation. In fact, the actual strata corresponding to those in the diagram are detrital turbidite sediments, consisting of well-sorted, fine-grained sands, which Steno likely saw in his travels around Tuscany.[45] The uniformity and fine size of the sediments, and the lack of visible fossils, convinced Steno of their primordial origin. Earlier in *De Solido* he writes:

> *If all particles in a stony stratum are observed to be of the same nature and of fine size, it cannot reasonably be denied that this stratum was produced at the time of Creation from a fluid that then covered all things: Descartes, too, accounts for the origin of the earth's strata in this way.*[46]

The second episode of deposition (22 in Figure 2) Steno attributes to the Deluge. Steno notes that mountains existed at that time, according to Scripture. The diagram shows first-cycle rock strata (F-G in Figure 2) at higher elevations than strata (B-A-C) deposited during the second cycle, so these presumably provided the source for these sediments. It is less clear, however, if Steno intends that all these strata formed during that single event, because in several places in *De Solido* he explicitly considers multiple marine incursions into Tuscany. Marine strata containing the "timbers of ships"[47] are clearly post-Diluvial, and Steno cites approvingly the ancient accounts of "earth movements, eruptions of fires from the earth, flooding by rivers and seas" as demonstrating that "many and various changes have occurred in four thousand years" since the Deluge.[48] It would appear then, that while Steno is careful to reconcile his scenario with Scripture, he conceives his rock cycle as not only a natural, but an ongoing process.

CONCLUSION

In Steno's geological works, *Canis* and *De Solido*, he lays out the elements of a functional, if in modern terms incomplete, rock cycle. Missing, of course, are igneous and metamorphic rocks, and he also gives little attention to the processes of lithification and weathering. However, the three key aspects of the rock cycle mentioned above are well-represented in Steno's work, especially in De Solido:

1. *Classification of rock by its mode of origin (generative classification).* Steno introduces this idea at the outset of *De Solido*, and he applies it in both works to argue for the sedimentary origin of rock strata, as well as to make the distinction between chemical and detrital sediments, and to discern sedimentary environments of strata. His principles of Molding and Sufficient Similarity, which form the basis of generative classification, would later find application to other rock types as well, such as plutonic igneous and metamorphic, of which Steno was unaware but are fundamental parts of the modern rock cycle.

2. *Derivation of rock from pre-existing Earth materials.* Steno is clear that sedimentary strata can be composed of recycled material eroded from older rock. Moreover, his principles of reasoning allowed him to recognize this material in strata. In contrast with modern understanding, however, he considers the oldest exposed rocks in Tuscany to be primordial and therefore a product of the original Creation.

3. *Cyclicity of process.* In *De Solido* Steno proposes natural mechanisms for uplift and sea level change. He also describes ongoing processes of erosion, transport,

[44] P. 205 in Ref 2 (Scherz)

[45] S. Dominici, Journal of Mediterranean Earth Sciences, **2009**, 1, 101-110.

[46] P. 163 in Ref 2 (Scherz). Steno's mention of Descartes refers to the model presented in Ref 33 (Descartes). In Descartes' model the solid particles producing the Earth's strata are "corpuscles" of matter, rather than sedimentary grains.

[47] P. 163 in Ref 2 (Scherz)

[48] P. 211 in Ref 2 (Scherz)

and sedimentation. Further, in his outline of Tuscany's geologic history, he recognizes two major cycles of sedimentation, and hints at later, smaller-scale cycles.

Steno's stated purpose in *De Solido* was to account for the existence of solid bodies, such as fossils and mineral crystals, inside of solid rock, not to create an overarching theory of the Earth. Still, despite some gaps and inaccuracies, Steno's rock cycle as it appears in his work, supported by his principles of Molding and Sufficient Similarity, constituted a forerunner of the modern rock cycle concept.

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Crystalline Stenonian Time Features from Earth and Beyond

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Abstract. The writings of Niels Stensen (Steno) on mineral growth and modification in his *Prodromus*, together with his work on time and process in other solids, are here synthesized as five classes of time features defined by changes in the visible continuity of either or both chemistry and orientation. This organization highlights Steno's implicit recognition of the fractal, scale-invariant nature of natural time features with regard to space, time, and material. The effectiveness of this Stenonian geochronology framework is demonstrated down to atom scale with modern case studies of the U-Pb geochronology of mineral zircon in samples originating from the Earth, Moon, and Mars spanning most of solar system history. Recently discovered nano-scale features, here termed chronostructures, were intimated by Steno in his corpuscular view of mineral behaviour. The remarkable advances in the *Prodromus* are seen here as resulting from the intersections of Steno's highly attuned approach to visual perception, his adoption of Stoic (Senecan) ethics early in his career to guide his natural philosophy, and the influence of the Galilean scientific environment of Florence. It is argued that the scale-invariant, intensive quality of Stenonian geochronology makes it an invaluable check on the accuracy of absolute, extensive measurements of geologic time by chemical or isotopic means. In this way Steno's scientific legacy continues to propel human understanding of how we see our place in time.

Keywords: Steno, crystal, zircon, geochronology, fractal, Stoic.

1. INTRODUCTION:

The geological writings of the famed anatomist Niels Stensen, mostly expressed in his "The Prodromus to a Dissertation on a Solid Naturally Contained Within a Solid" (hereon referred to as the *Prodromus*),[1] have been seen as foundational to the current fields of stratigraphy, palaeontology and crystallography through his elucidation of the principles of sedimentary superposition, the organic origin of fossils, and the law of angular con-

[1] N. Stensen, *De Solido Intra Solidum Naturaliter Contento Dissertationis Prodromus,* Florence, Stella, **1669** (*Prodromus* in following notes). English translation in T. Kardel, P. Maquet, *Nicolaus Steno, Biography and Original Papers of a 17th Century Scientist*, 1st edition, Heidelberg, Springer, **2013** (K&M in notes below), pp. 621-660,

stancy in crystals, respectively. Steno's 'founder' status, however, is seen by some historians of science as anachronistic,[2] given that his authorship of these ideas was ignored for more than a century before acknowledgement in later retrospectives of geography and geology.[3,4] More recent historians of science have commented that Steno's *Prodromus* was principally an advance in the cognition of geologic time.[5,6] Steno's novel and detailed descriptions of mineral growth have received renewed attention[7], and in this paper I propose that his influence on the field of geochronology likewise merits greater recognition, particularly in light of the continuing application of Stenonian methods. With Steno's mineralogy as a starting point, I have used his observations of time information in all solids to derive a classification scheme for Steno's vision-based geochronology. The modern relevance of this scheme is illustrated with microscopy case studies, down to atom scale, of the weakly radioactive geochronology of mineral zircon in samples from Earth and other planetary bodies spanning most of solar system history. This is followed by a consideration of Steno's method of observational science in the context of his European education and association with the Galilean *Accademia del Cimento* to explore reasons why Steno was able to perceive geologic time hidden from most others. Finally, the continuing importance of Steno's approach to the accuracy of both relative and absolute geochronology is discussed. It is hoped that, as it did for me, this treatment links Earth scientists and geochronologists more clearly to our observational and philosophic roots as well as to an awareness of the 17th century brilliance of Steno working in the Galilean tradition.

Relative and absolute geochronology - then and now

Geochronology is taken here to be the science of measuring time information from natural materials and to be of two types; relative, establishing the numerical order of events, and absolute, the age of an event or interval referenced to units of years. In the age of Steno, and particularly in the *Prodromus*, the relative and absolute times for events in Earth history were based on natural philosophy and biblical scripture, respectively, and were not seen to intersect or conflict as they were derivatives of independent logic systems[2,8] with which Steno presented faith and natural history as separate domains of knowledge.[9] Steno's natural philosophy was likely influenced by that of Aristotle, in view of his adaptation of Aristotelian form and argument in his early work on hot springs, *De Thermis*[10]. Sambursky provides a concise summary of Aristotelian philosophy regarding relative and absolute time:

> *Aristotle's definition* "time is number of motion in respect of 'before' and 'after'"—*expresses both the association of time with change and the possibility of enumerating this change. It is also evident from his analysis that he realized that the prerequisite for time measurement is a clock, i.e., a periodic mechanism, and that the revolution of the celestial sphere, being a regular circular motion, is the best measure of time* "because the number of it is the best known".[11]

As noted by many authors, Steno declined assigning absolute ages directly to natural solids as on this topic "nature says nothing",[12] but he nevertheless played a pioneering role in ordering sedimentary strata in respect to the directional arrow of time.[13]

The 19th century saw the ascendence of absolute geochronology after the discovery of the laws of radioactivity and techniques for measuring ratios of elements and their isotopes in rocks and minerals.[14] The first measurement of the absolute ages of sedimentary strata is widely attributed to Holmes[15] who compared

[2] M. J. S. Rudwick**,** *The Meaning of Fossils. Episodes in the History of Palaeontology*. London, MacDonald, London, & New York, American Elsevier Inc., **1972**, 287 pp.

[3] N. Desmarest**,** *Géographie physique*. 4 vols. Paris, **1794** [Encyclopédie méthodique].

[4] C. Lyell, *Principles of Geology: being an attempt to explain the former changes of the Earth's surface, by reference to causes now in operation*. London, John Murray, 1, **1830**.

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[6] S. J. Gould, The titular bishop of Titiopolis. *Natural History*, **1981**, *90*, pp. 20–24; reprinted in *Hen's teeth and horse's toes*, New York, Norton's Paperback, **1983**, pp. 69–78.

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[12] N. Stensen, *Prodromus*, in ref. 1 (K&M), p. 654.

[13] G. Kravitz, The geohistorical time arrow: from Steno's stratigraphic principles to Boltzmann's past hypothesis, *Journal of Geoscience Education*, **2014**, *62*, p. 691-700.

[14] E. Rutherford, E., & F. Soddy, *J. Chem. Soc.*, **1902**, *81*, p. 837; reprinted in *Phil. Mag.*, **1902**, *4*, p. 370; **1903**, *5*, p. 576.

[15] A. Holmes, The association of lead with uranium in rock-minerals, and its application to the measurement of geological time. *Proceedings of the Royal Society of London A*, **1911**, 85, p. 248-256.

the relative (Stenonian) geochronology of a section of early Paleozoic sediments in Norway to absolute ages calculated from the U and Pb abundances in minerals (including zircon ($ZrSiO_4$)) from inter-layered and cross-cutting igneous (once molten) rock bodies. Critically, Holmes established the premise of the "closed system" for absolute methods; stipulating that an age measurement is only accurate if the sampled volume has remained closed to chemical alteration since its production aside from change due to radionuclide decay. In this light, and in the terminology of thermodynamics, every absolute geologic age is an extensive property of a solid. The extent of the systems in Holmes' pioneering work were mineral grains containing U and its radiogenic Pb. As we will see, it is due to this extensive property that the accuracy of absolute methods relies, ultimately, on Steno's relative approach.

Minerals are defined by the International Mineralogical Association as the inorganic building blocks of rocks, each characterized by a particular chemical composition and a defined crystal structure. These commonly occur as polyhedral bodies such as the cm-scale specimens described in the *Prodromus*. Steno classed minerals as "angular solids", and focused on samples of "crystal" (quartz) and "iron" (hematite, pyrite) which he collected from the Tuscany region, Elba, and other localities in central Europe[16]. Absolute geochronology using the U-Th-Pb decay chains has become the benchmark for calibrating the time scale for the Earth[17] and solar system,[18] and the U-bearing mineral zircon plays a major role.[19]

Zircon occurs widely in the crusts of rocky planets, mostly as microscopic grains forming accessory components in rocks over a depth range on the order of 100 kilometres. The primary features of each grain can withstand erosion, mountain building events, transport in magmas, plate tectonic cycles, and meteorite impacts; all the while accumulating either or both external and internal features that bear witness to these events.[20] Zircon crystals commonly have the width of a human hair, an order of magnitude smaller than Steno's cm-scale samples (Fig. 1), yet zircon grains have the distinction of being the oldest known pieces of the Earth,[21] Moon[22] and Mars.[23] Zircon also has a different crystal structure in comparison to Steno's quartz (tetragonal vs. hexagonal) however it exhibits a similar, long-prismatic habit such that it is weakly to strongly columnar, sharing "intermediate" (prismatic) and "terminal" (pyramidal) faceting reported by Steno.[24] Zircon exhibits internal zoning when a cross-sectional surface is imaged with a scanning electron microscopy and a cathodoluminescence detector (SEM-CL).[25] These zones are analogous to the colour changes noted by Steno in his quartz cross sections of "the plane in which the axis of the crystal lies"[26] (Fig 1). Steno's cross-sectional depictions were novel in his time, marking a transition from 'organic' to 'mechanical' mineralogy',[27] whereas such cross-sectional crystal imaging is now a routine component of petrology and absolute zircon geochronology.

Previous work on Stenonian geochronology

The framework which Steno describes in the *Prodromus* for interpreting the Earth resolved not only the immediate question of the nature of fossils, and discriminating their found location from their place of production, but presented a logic structure for identifying geologic time sequences from features discernible in solids.[28] Steno's authorship of this structure was largely ignored among later theories of the Earth although his concepts and ideas carried on in the work of others such as Leibniz[29] or were tested and transmitted by later Italian geologists.[30] Receiving most attention was his princi-

[16] N. Stensen, in ref. 1 (K&M), p. 208.

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[26] N. Stensen, in ref. 1 (K&M), p. 659.

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[28] M. J. S. Rudwick, *The meaning of fossils. Episodes in the history of palaeontology*. London, MacDonald, London, & New York, American Elsevier Inc., **1972**, 287 p.

[29] D. Garber, Steno, Leibniz, and the history of the world, in ref. 8, p. 201-232.

[30] S. Dominici, Steno, Targioni and the two forerunners. *Journal of Mediterranean Earth Sciences*, **2009**, *1*, p. 101-110.

ple of 'moulding'[31] which had been denoted in the 18th century by Desmarest as Steno's "*Premier Principé*". [32] Among the most detailed modern assessments of Steno's work regarding relative geochronology is that of Hansen[33] who recognized in Steno's writings the "cognition criteria" of chronology, recognition (i.e. resemblance), and preservation. Chronology was subdivided into the principles of moulding and intersection. Moreover, two underlying axioms related to the quality of orientation were proposed in terms of "conformity," and "disconformity." Steno's interpretation of what had been viewed previously as "signs" in natural materials[34] were termed "structural", underpinning a further five principles of geological interpretation leading to "back-stripping" to reconstruct crustal dynamics over time. These organizations of Steno's work on solids were interpreted predominantly from his macroscopic observations of sediments, and, while valid and self-consistent, did not incorporate many of Steno's observations of minerals and mineralized bodies such as agate ("incrustations"). When these too are considered, and paired with Steno's atomistic (corpuscular) view of crystals,[35] additional Stenonian insights become apparent.

2. METHOD AND MATERIALS

The *Prodromus* has been called "a complex and odd little book",[36] and in his introductory text Steno does apologize to his patron for any seeming disorganization due to the constraints of time and travel. My analysis initially relied on the English translation of the *Prodromus* by Winter[37], but then mainly fell to translations of the much broader compilation of Steno's works translated by Kardel and Maquet,[1] all of which were approached in several ways. First, all indications, whether in the text or diagrams, of time, motion, and process observed or deduced from natural solids, were noted with particular attention to Steno's descriptions of minerals and incrustations in the *Prodromus*. The visual-cognition term 'feature' (see definition below) was then used to subdivide Steno's descriptions of temporal phenomena into classes according to chronology, process, and underlying material properties causing continuity, or disruption, of either or both chemistry and geometric orientation (Table 1). The sources of translated Steno quotes in Table 1 regarding Minerals and Strata occur in the main body of text, whereas the remainder are as follows for Fossils[38] and Incrustations.[39] Note that the S_5 class descriptor is based on a translation from Hansen (2009) in Ref. 8. Detailed class descriptions with relevant translations of Steno are presented alongside modern microscopy results for the U-Pb geochronology of the mineral zircon. All microscopy was performed by the author's research group and collaborators using previously described electron beam techniques[40] at the University of Western Ontario or using previously described atomic imaging techniques[41,42] at the Canadian Centre for Electron Microscopy, McMaster University.

Terminology for Stenonian time features

The term *feature* has been used here to generalize the different signs or visual patterns which Steno ascribed to the effects of time's passage during the production or alteration of solid materials. Steno's raw visual observations are mostly expressed as geometric surfaces, with the word 'surface' here used according to the mathematical definition; a generalization of all planes which may or may not have some amount of curvature. Steno's geometric descriptions of surfaces in the *Prodromus* followed either Euclidean geometry or projective geometric representations of the Platonic solids in the tradition of Pierro, Kepler and Dürer,[43] and his single plate of diagrams[44] combines these approaches. Notably,

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[31] S. J. Gould, S.J. in ref. 6.
[32] N. Desmarest in ref. 3.
[33] J. M. Hansen, On the origin of natural history: Steno's modern, but forgotten philosophy of science, in ref. 8 (Rosenberg), p. 159-178.
[34] T. Yamada, Kircher and Steno on the "geocosm", with reassessment of the role of Gassendi's works, in *The origins of geology in Italy* (Eds. G. B. Vai, W. G. E. Caldwell), Geological Society of America Special Papers, **2006**, *411*, p. 65–80.
[35] W. C. Parcell, Signs and symbols in Kircher's *Mundus Subterraneus*, in ref. 7 (Rosenberg*)*, p. 63-74; C. J. Schneer, Steno on crystals and the corpuscular hypothesis, dissertations on Steno as geologist. *Acta Historica Naturalium et Medicinalium*, **1971**, *34*, p. 293–307.
[36] R. Rappaport, in ref. 10, p. 202.
[37] J. G. Winter, *The prodromus of Nicolaus Steno's dissertation concerning a solid body enclosed by process of nature within a solid*. University of Michigan studies: Humanistic series, Macmillan, **1916**, 115 pp.
[38] N. Stensen, in ref. 1 (K&M), p. 647-648.
[39] N. Stensen, in ref. 1 (K&M), p. 630.
[40] D. E. Moser, C. L. Cupelli, I. R. Barker, R. M. Flowers, J. R. Bowman, J. Wooden, J. R. Hart, New zircon shock phenomena and their use for dating and reconstruction of large impact structures revealed by electron nanobeam (EBSD, CL, EDS) and isotopic U-Pb and (U-Th)/He analysis of the Vredefort dome. *Can. J. Earth Sci*., **2011**, *48*, p. 117-139.
[41] J. R. Darling et al., Variable microstructural response of baddeleyite to shock metamorphism in young basaltic shergottite NWA 5298 and improved U-Pb dating of Solar System events. *Earth Planet. Sci. Lett.*, **2016**, *444*, p. 1-12.
[42] G. A. Arcuri, D. E. Moser, D. A. Reinhard, D. Larson, B. Langelier, Impact-triggered nanoscale Pb clustering and Pb loss domains in Archean zircon. *Contributions to Mineralogy and Petrology*, **2020**, *175*, p. 59, 1-13.
[43] C. J. Schneer, in ref. 35.
[44] N. Stensen, in ref. 1 (K&M), p. 658.

and, perhaps unique for his time, are his two-dimensional projections and juxtaposition of three-dimensional geologic entities, such as sedimentary strata and growth layers within crystals, into a Euclidean plane which contains either the downward vector of Earth's gravity or the principal (central) axis of crystal growth. Steno does not refer to most of these features in formal geometric terms but as nouns with embedded actions. He does not, for instance, refer in Latin to a sedimentary deposit as a *planum* (plane), but as a *stratum*- the past participle of *sternere* "to spread out". Action, motion, and thus time, thereby become embedded meanings in his descriptor of a planar, natural feature.

Some have referred to parts of Steno's drawings as "structures", particularly the ruptured strata in his cross-sections of Tuscany;[45] however, this term derives from *structus*, the past participle of *struere* "to pile,… assemble", whereas, at mineral grain or crystal lattice scales, these features are more accurately described by voids or a breakdown of order. As discussed below, Steno's methods are primarily visual, and consequently the visual term 'feature' is adapted here to encompass true structures and other types of recognizable material changes in solids. A '*feature*', when used in regard to material objects, is defined in English as "some part which arrests the attention by its conspicuousness".[46] Time is implicit in this definition - not in regard to the passage of time during production of the object but of time elapsing during the act of its observation during which the mind's attention is arrested. This process of observation will be discussed later in the context of Steno's methodology.

4. RESULTS

Upon consideration of Steno's observations of all natural solids, five classes of Stenonian time features signifying production or modification can be described, along with a brief mention of a sixth 'origin' class (Table 1). The first two classes of Stenonian time features can be considered as one or more Euclidean planes in that they, at length scales of observation typical in geology, are surfaces with zero curvature at any point. For Steno's "crystals" the planes in his diagrams are two-dimensional projections of symmetrically-related set of crystal facets analogous to sedimentary strata (Fig. 1). Together they are the primary features of production and establish the reference features for discriminating later, modifying processes and events. The other three feature classes represent, at some scale, disruptions in continuity; what Steno described in the case of tilted strata as "obvious inequalities" [47] of angle with respect to the horizon and the gravitational field. At the atomic level in minerals, such discontinuities fall into two broad groups: discontinuity in chemistry, while maintaining crystalline order, and discontinuity due to a breaking or re-orienting of atomic bonds without necessarily changing the chemical composition. Each class is denoted with "S" for Steno and a subscript identifying the class number, and is described along with comparable features in zircon crystals.

a) S_0, S_1 *Features representing growth, hiatus, environmental change*

With regard to the beginning of the formation of a solid, Steno acknowledges that such a place must exist but would not speculate further. For minerals he stated that: "There may still be doubt about the place in which the first crystal begins, whether it be between fluid and fluid or between fluid and solid or in fact in a fluid by itself",[48] and strata are described only as being preceded by a global fluid. Nevertheless Steno acknowledges the existence of a beginning point and it is represented in this scheme as S_0, the first point of production which, for minerals, is taken as the geometric centre of zoning (Fig. 1). From there he recognized, in different places in his writings on solids, subclasses of S_1 features to which he attributed vectors, pauses, and environmental changes during production.

Vectors and nature of growth processes

Steno's view of mineral growth shared some similarities with sedimentary strata but with important differences in the kinetics of growth. In both solids he saw that; "The growth of all solids is from fluids" and that a body "grows by addition of new particles".[49] Hearkening to his choice of the term *stratum* for sedimentary layers, Steno indicates that "new crystalline material, added to the crystal, is spread out over a plane"[50] with the important difference that "buoyancy or gravity are not involved",[51] and crystal growth is instead driven by "the subtle fluid permeating all matter"[52]. Thus gravity controls sedimentation in a single, vertical field, whereas particle addition in another field causes crystals to grow

[45] J. M. Hansen in ref. 33.
[46] "feature, n." *OED Online*, Oxford University Press, December 2020, www.oed.com/view/Entry/68848.

[47] N. Stensen, in ref. 1 (K&M), p. 653.
[48] N. Stensen, in ref. 1 (K&M), p. 639.
[49] N. Stensen, in ref. 1 (K&M), p. 630.
[50] N. Stensen, in ref. 1 (K&M), p. 642.
[51] N. Stensen, in ref. 1 (K&M), p. 634.
[52] N. Stensen, in ref. 1 (K&M), p. 631.

Table 1. A classification scheme for Stenonian time features in solids (top row) based on representative Steno descriptions symbolized as; "**quotations from Steno (transl.)**", 'author's condensation of translated text', and [modern terminology]. Arrows represent cases where features in strata are now known to have analogous mineral features. *Far left column identifies the quality of the continuity change across each feature relative to its surroundings as; chemical (C) , geometric orientation (O) or a combination of either or both (C||O). See Methods for sources of translated Steno quotations.

		"**Angular solids**" [Minerals]	"**Strata**"	[Fossil]	"**Incrustations**" [Concretions]
*	Stenonian time feature class				
C	S_5; intra-solid diffusion	smallest particles in "**inner revolt**"	[metamorphism]		
O	S_4; deformation (brittle, rapid)	<—	"**shattering**" causing "**obvious inequalities**" in angles		
O	S_4; deformation (plastic, slow)	<—	"**subsidence**", "**twisting into curves**"		
C||O	S_3; mechanical erosion	"**fractured sides**"	[erosional unconformity]		
C||O	S_3; chemical erosion	dissolution "**cavity**" leaving "**lamellae**"	[chemical unconformity]	'shell partly destroyed, eaten away'	
C||O	S_2; end of production	surface of "**angular solid**", form related to 'constancy of angles'	"**upper surface is parallel to the horizon**" final form related to gravity	"**outer edge of the animal**"	'outer surface of concretion' controlled by roughness of place
C	S_1; hiatus in production	"**if…crystal contained by crystal**" then "**contained bodies already hard**"	'fluid recession, sediment hardening, and fluid return'		
C	S_1; growth and environmental change during growth	"**crystal grows while new crystalline material is added to the already formed crystal**" colour zoning due to "**ingress of new material**"	strata differences due to "**different kinds of fluid from different places through that spot at different times**"	'**imprint on each margin of the testulae**'	
C	S_1; growth domain	crystal layer created by "**addition of new particles in succession**"	"**stratum**"	"**testulae**" mollusc shells	"**fluid directs material to the solid on all sides**"
	S_0; start of production	"**doubt about the place in which first hardening of the crystal begins**" [nucleation]	"**Creation from a fluid that covered all things**"	point of nucleation 'seed'	

along several, mathematically related directions. Steno analogized crystal growth with particles aligning like iron filings in a magnetic field such that "both the number and length of the sides are changed in various ways without the angles being changed."[53]. Flow in the mineral's parent liquid did not alter the direction of the field driving crystallization in that "the movement of crystalline material […] depends on the movement of the tenuous fluid that flows from the already formed crystal". [54]

Successional growth

Among the most important spatiotemporal deductions by Steno was that of the successional growth of lay-

[53] N. Stensen, in ref. 1 (K&M), p. 642, also ref. 41.

[54] N. Stensen, in ref. 1 (K&M), p. 642.

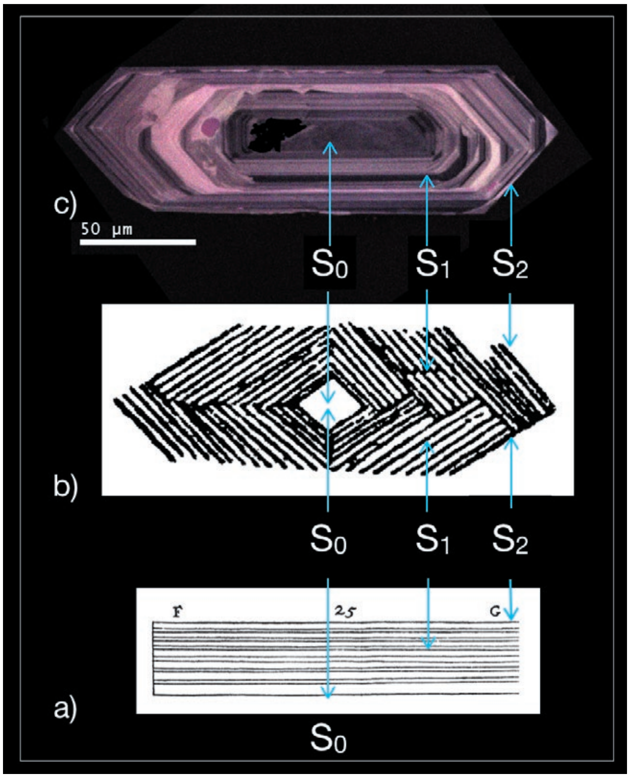

Figure 1. Stenonian time features of production (S_0, S_1, S_2; see text) from Plate 1 of the *Prodromus*[1] showing a) undeformed strata (km-scale), b) growth zones in sectioned quartz (cm-scale) and c) SEM-CL image of a polished section through a zircon microcrystal (note scale bar 5 micrometre scale bar). [1] N. Stensen, in ref. 1 (K&M), p. 658.

ers in solids. For minerals he noted that "crystal growth was not vegetative"[55] as in herbaceous plants. His argument against the vegetative mineral growth hypothesis can be traced to his discussion of the growth layers within the class of solids he termed "incrustations" (i.e., agates, geodes). He describes the "differences in layers" in these solids with the important time descriptor of relative age; "succession".[56] He recognized the curviplanar geometry and extension of the concentric layers in these "stones composed of layers the two surfaces of which are indeed parallel but are not extended in the same plane". He then compared these to the concentric, curviplanar growth layers in non-herbaceous woody plants "where they show the round veins of a tree cut transversely".[57] Steno contrasts these processes for mineralized bodies with those giving rise to strata, stating that:

> *Additions [of particles] made directly to a solid from an external fluid sometimes fall to the bottom because of their own weight, as in the case of sediments; sometimes the additions are made from a penetrating fluid that directs material to the solid on all sides, as in the case of incrustations.*[58]

The outward growth of minerals is now universally recognized and utilized in the fields of petrology and mineralogy in which rocks and minerals are examined in polished, transparent sections, and likewise in zircon geochronology where SEM-CL microscopy is used to reveal S_1, concentric growth banding. These represent changes in trace element chemistry inherited from the magma and are expressed as variations in luminescent intensity and/or colour (Fig 1). The orientation of the crystal lattice across the chemical zoning does not change such that banding marks discontinuities in chemistry within a zone of continuous crystal orientation.

Time gap (hiatus) in growth

"Stony strata are found between earthy strata" due to a "fluid, having receded from the sediment that had been deposited, returned again when the upper crust had become hardened by the heat from the sun".[59] Beyond outward growth, Steno recognized that both the conditions and rate of growth can vary during the production of natural solids. Drawing on his writings on strata, he clearly envisions a scenario wherein either or both a time gap and changes in the formative environment results in variations in visual properties across a set of layers. In his second proposition he states, "if at any time a crystal is partly enclosed by a crystal, a marcasite by a marcasite, then at a time when these contained bodies were already hard, part of the containing body was still fluid".[60] A corresponding recognition of hiatus in sedimentation was also noted as possible (above). We now know that concentric, apparently continuous, zoning sequences within zircon grains released from a single volcanic eruption lasting days can, in some cases, represent age differences of hundreds of thousands of years; their S_1 features a product of halting outward growth over this period. The crystal shown in Fig.1 is representative of those from a Cretaceous ash layer, now exposed in the Canadian Rocky Mountains. Absolute dating of such grains indicates that the zoning represents up to sev-

[55] N. Stensen, in ref. 1 (K&M), p. 640.
[56] N. Stensen, in ref. 1 (K&M), p. 634.
[57] N. Stensen, in ref. 1 (K&M), p. 633.
[58] N. Stensen, in ref. 1 (K&M), p. 630.
[59] N. Stensen, in ref. 1 (K&M), p. 635.
[60] N. Stensen, in ref. 1 (K&M), p. 629.

eral hundred thousands of years of crystallization prior to eruption[61].

Environmental change during growth

> *Difference in layers at the same place can be produced either by the diversity of particles leaving the fluid in succession, as this fluid is gradually dissipated more and more, or by different fluids being conveyed there at different times: so it happens that sometimes the arrangement of layers is repeated in the same place, and often evident signs exist showing the ingress of new material.* [62]

Steno was careful to distinguish "place" (i.e., the place or environment where a solid was produced) from the "location", or site of discovery of that solid, recognizing that "location does not explain production".[63] In the case of strata, Steno also recognized that changes in the sedimentary section could reflect changes in sedimentary conditions and sources through time, and that stratal changes vertically result from "different kinds of fluid from different places through that spot at different times". Similarly for minerals, Steno understood that the place of production imbues solids with signatures of their native environments, such that "Rocks of different types, emitting different fluids, produce crystals of different colours"[64]. Moreover, Steno realized that even in the place of production, an environment of crystallization can change during the growth such that "sometimes in the same crystal the parts first hardened are sometimes darker than those hardened last".[65] We now know that igneous minerals commonly show internal compositional layering due to very local effects of growth-limiting elements among other factors such as surface energy, magma viscosity, and temperature, as is known for both quartz[66] and zircon.[67]

b) *S_2 final form at end of production*

A second class of Stenonian time feature is defined as the exterior or upper surface of a solid at the completion of its growth in the place of production. For minerals crystallizing from a liquid, S_2 is a polyhedral surface composed of Euclidean planes (crystal growth facets) the orientations of which follow Steno's law of angular constancy. Figure 2 illustrates Steno's method of projecting this three dimensional surface such that "all the 12 planes laid out in one plane" [68] and neighbouring crystal facets connected by a shared vertex. He recognized it as a time marker implicitly in his use of it to infer order of crystal growth (above). It should be noted that Steno did not consider metamorphic minerals, i.e. crystals that grew while most of its surroundings were solid. The S_2 surface of such grains reflects some combination of growth processes and surface energies among surrounding mineral phases[69]. In either case, the final, outer surface represents a discrete point along time's arrow. This is at once the simplest and perhaps most important time feature for Steno's interpretation of fossils as it occurs at the meeting place of an object with its surroundings (rock, air, etc.) at its present location (Table 1). The S_2 feature class includes the uppermost surface of a stratum, the final form of an organism, or the outermost atomic layers of a crystal. This was the key time feature used to discriminate between an allocthonous (transported from elsewhere) vs. autochthonous (formed *in situ*) origin for Steno's fossils relative to their found location (i.e. Desmarest's *Premier Principé*). This feature is of central importance in the *Prodromus* and remains a key tool in the modern geochronologic interpretations of minerals such as zircon as to whether or not they are endogenic or exotic to their current setting.

c) *S_3 modifications of original form*

The S_3 class of features, along with the other two remaining classes, share the characteristic of being surfaces marking discontinuities in one or both of chemical composition and crystallographic (atomic) orientation, with the change occurring over a length-scale much less than that of the relevant surfaces.

S_3 due to chemical erosion (dissolution)

> *just as a crystal has formed from a fluid, so that same crystal can be dissolved in a fluid, provided one knows how to imitate nature's true solvent.*[70]

Following on his basic statement that all solids grow from fluids, Steno concludes that the process can operate in reverse (above). It is plausible that Steno shows

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[61] I. R. Barker, D. E. Moser, S. Kamo, G. Plint, High-precision U–Pb zircon ID–TIMS dating of two regionally extensive bentonites: Cenomanian Stage, Western Canada Foreland Basin. *Can. J. Earth Sci.*, **2011**, *48*, p. 543–556.

[62] N. Stensen, in ref. 1 (K&M), p. 634.

[63] N. Stensen, in ref. 1 (K&M), p. 628.

[64] N. Stensen, in ref. 1 (K&M), p. 641.

[65] N. Stensen, in ref. 1 (K&M), p. 641.

[66] D. A. Wark, B. E. Watson, TitaniQ: a titanium-in-quartz geothermometer. *Contributions to Mineralogy and Petrology*, **2006**, *152*, p. 743-754.

[67] P. W. O. Hoskin, Patterns of chaos: Fractal statistics and the oscillatory chemistry of zircon. *Geochimica et Cosmochimica Acta*, **2000**, 64, p. 1905-1923

[68] N. Stensen, in ref. 1 (K&M), p. 659.

[69] R. Kretz, On the spatial distribution of crystals in rocks. *Lithos*, **1969**, *2*, p .39-69.

[70] N. Stensen, in ref. 1 (K&M), p. 643.

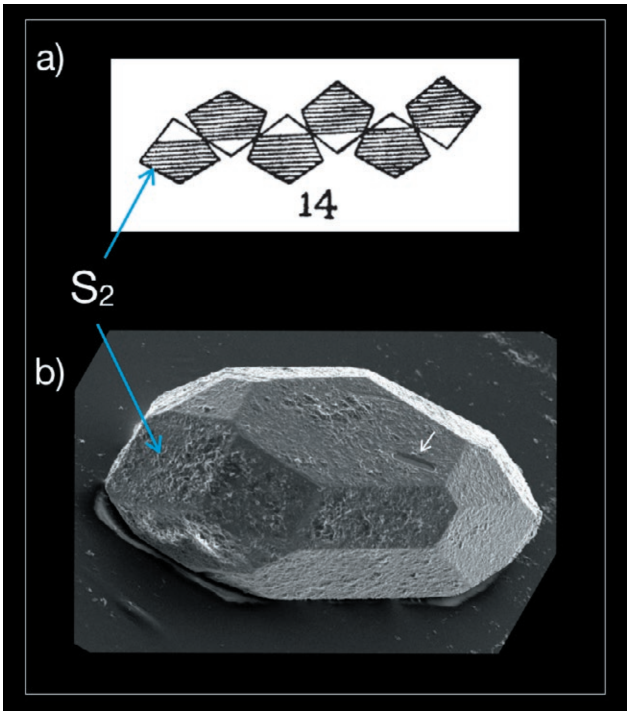

Figure 2. Two views of Steno's final surface of production (S_2) in minerals; a) Steno's two dimensional representation of the external, Euclidean planes of an '*iron*" crystal (marcasite) b) An SEM image of a euhedral, igneous zircon crystal, same sample as in Figure 1c (grain length = 250 micrometres). Note the mould of a smaller grain (white arrow), likely the mineral apatite, encountered during the last increment of growth before eruption.

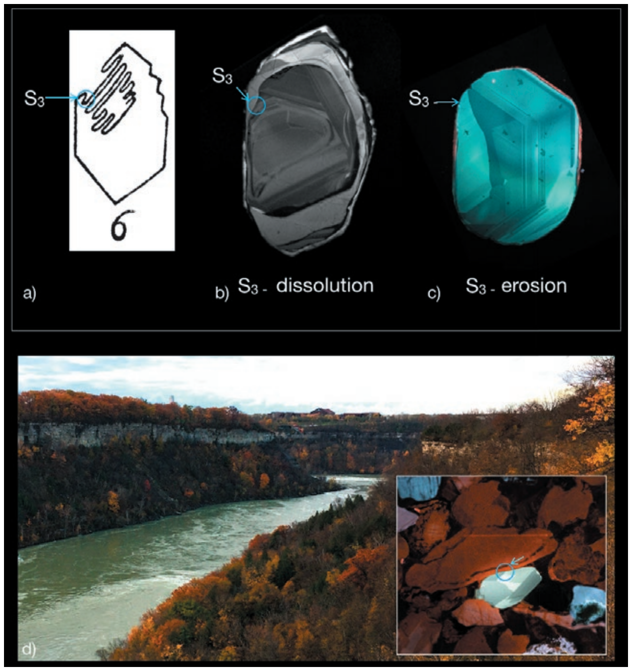

Figure 3. Features of modification: a) Steno's quartz crystal and a surface of S_3 chemical dissolution. Zircon SEM-CL images showing b) 4.02 billion year S_1 growth features truncated by a S_3 dissolution (metamorphic) surface, c) a zircon from beach sand with external S_3 surface of mechanical erosion. d) Southward view from Canada of the Niagara River Gorge and the type locality for the Silurian Whirlpool sandstone; Inset, SEM-CL image of rounded zircon sand grain among quartz grains (red), Whirlpool sandstone. All zircon grain lengths ~ 300 micrometres.

the effects of dissolution in his Diagram 6 where he describes "*th*at various cavities are left in the very middle of the crystal and various lamellae are formed."[71] (Fig. 3). This diagram could be interpreted to show a partly dissolved quartz crystal with lamellae of relict growth layers (S_1) from the originally continuous solid body. Alternatively, the lamellae could represent a face of relatively slow crystal growth frustrated due to surface kinetic effects. Regardless, it is clear that Steno anticipated dissolution during natural processes. Resorption surfaces similar to the forms in Steno's drawing were produced in zircon by Prof. Thomas Krogh in laboratory etching experiments [72] and rounding of originally equant zircons due to metamorphic fluids in the crust is now widely documented.[73] Often this stage of resorption is followed by renewed zircon growth continuous in lattice orientation (i.e. epitaxial growth), but different in chemical composition (Fig 3). This creates a feature visually akin to an angular unconformity in strata, as shown in a 4.02 billion year old zircon from Earth's oldest known rock (Fig. 3).[74]

S_3 due to mechanical erosion

> "*nor have I ever seen a crystal whose still unbroken surfaces have the smoothness that the fractured sides of the same crystal show after it has been broken apart.*"[75]

Steno was clear that a solid body could form in one place and move to another unrelated to its genesis: "since the earth bestows location at least in part to all

[71] N. Stensen, in ref. 1 (K&M), p. 646.

[72] D. W. Davis, I. Williams, T.E. Krogh, Historical development of zircon geochronology. *Reviews in Mineralogy and Geochemistry*, **2003**, *53*, p. 145-181

[73] M. J. Kohn, N. M. Kelly, Petrology and geochronology of metamorphic zircon, in *Microstructural geochronology: planetary records down to atom scale* (Eds. D. E. Moser, F. Corfu, J. R. Darling, S. M. Reddy, K. T. Tait), Hoboken, NJ, Wiley, **2017**, p. 35–61.

[74] J. R. Reimink, T. Chacko, R. A. Stern, L. M. Heaman, Earth's earliest evolved crust generated in an Iceland-like setting. *Nature Geoscience*, **2017**, *7* , p. 529-533.

[75] N. Stensen, in ref. 1 (K&M), p. 642.

the things of the earth, the location by itself does not explain the production of a body".[76] He recognized that "Mountains can be destroyed",[77] that cavities can be filled with "earthy material eroded from higher places by the continuous rainfall",[78] and that the particles in sediments sink under their own weight even if "conveyed there from elsewhere".[79] In his series of strata cross-sections he notes "hills and valleys produced there by the destruction of the upper sandy strata".[80]These clues to motion and erosion on the outer surface of the Earth were also noted for crystals,[81] and the incrustations:

> *Incrustations are observed to be rough like ordinary stones on the outer surface, since the outer surface of the outer layer depicts the roughness of the place; in torrents, however, incrustations of this kind are often found away from the place of production because the material of the place has been scattered by the bursting of the strata.*[82]

Steno recognized the difference between growth faces and those modified by breakage (above) and this is a second type of intersection relationship with the original outer form or surface (S_2); one that is due not to dissolution of particles in a surrounding fluid but to mechanical abrasion or breakage during transport which modifies the original form causing an interruption in the continuity of the internal features when viewed in section (Fig. 3). Zircon grains are extremely resistant to chemical and mechanical breakdown, and the oldest known pieces of the earth are fine, sand-sized grains of zircon in much younger, though still ancient, sediments.[83]

e) S_4 features due to episodes of deformation

> *The earth's strata can alter position in two ways. The first way is the violent upheaval of strata, whether this be due mainly to a sudden flare of subterranean gases or to a violent explosion of air caused by other great subsidence nearby. This upward thrust of strata is followed by a dispersal of earthy material as dust and the shattering of rock material into pebbles and rough fragments. The second way is the spontaneous slipping or subsidence of the upper strata after they have begun to crack because of the withdrawal of the underlying substance or foundation;* […] *While some remain parallel to the horizontal, others become vertical; many make oblique angles with the horizon and not a few are twisted into curves because of the tenacity of their material.* [84]

Whereas Steno described deformation of the exterior of minerals, he did not remark on internal effects; so, for this class of time feature, we look to his insights gained from sedimentary strata and compare these to modern studies of zircon. As seen in the above quote Steno made some highly astute observations, recognizing two styles of deformation of strata and their respective geometric and material consequences. Steno was accurately describing the range of mechanical responses to different rates of deformation. He did not depict the first style in the *Prodromus*; that of violent, or very rapid, deformation but it is likely he was referring to the consequences of volcanic activity. The most extreme strain rate events now known to affect planetary crusts occur at the deepest levels of tectonic collision zones, and, at the most extreme end of the spectrum, within large meteorite impact craters as illustrated here with terrestrial and lunar zircon (Fig. 4).

S_4 due to rapid deformation

Zircon is one of the minerals most resistant to destruction by impact-related shock metamorphism, yet grains develop long-lasting and unique deformation features.[85] Fracturing and crystal distortions occur in microseconds and often under extreme, short-lived temperatures of up to a few thousand degrees Celsius. Disordered mineral glasses, instead of secondary minerals, can fill crystallographic fractures, a material difference alluded to by Steno: "the main cause of variation by which crystal differs from glass not only in refraction but also in other properties, since, in glass, no parts of the dissolving fluid are present, as they have driven forth by the violence of fire".[86] This deformation style of S_4 features has been recognized at the Vredefort crater in South Africa, offsetting S_1 growth zoning and S_2 surface of production (Fig. 4). We see a similar sequence in the features of >4 billion year old lunar zircons, including those recovered by the U.S. Apollo 17 mission near Steno Crater[87] (Fig. 4). In both cases, the zircon lattice

[76] N. Stensen, in ref. 1 (K&M), p. 628.
[77] N. Stensen, in ref. 1 (K&M), p. 637.
[78] N. Stensen, in ref. 1 (K&M), p. 656.
[79] N. Stensen, in ref. 1 (K&M), p. 634.
[80] N. Stensen, in ref. 1 (K&M), p. 660.
[81] N. Stensen, in ref. 1 (K&M), p. 640.
[82] N. Stensen, in ref. 1 (K&M), p. 633.
[83] J. W. Valley et al., in ref. 21.
[84] N. Stensen, in ref. 1 (K&M), p. 636.
[85] D. E. Moser, C. L. Cupelli, I. R. Barker, R. M. Flowers, J. R. Bowman, J. Wooden, J. R. Hart. New zircon shock phenomena and their use for dating and reconstruction of large impact structures revealed by electron nanobeam (EBSD, CL, EDS) and isotopic U-Pb and (U-Th)/He analysis of the Vredefort dome. *Can. J. Earth Sci.*, **2011**, *48*, p. 117-139.
[86] N. Stensen, in ref. 1 (K&M), p. 643.
[87] B. Zhang et al., Imbrium Age for Zircons in Apollo 17 South Massif Impact Melt Breccia 73155. *JGR Planets*, **2019**, *124*, p. 3205-3218

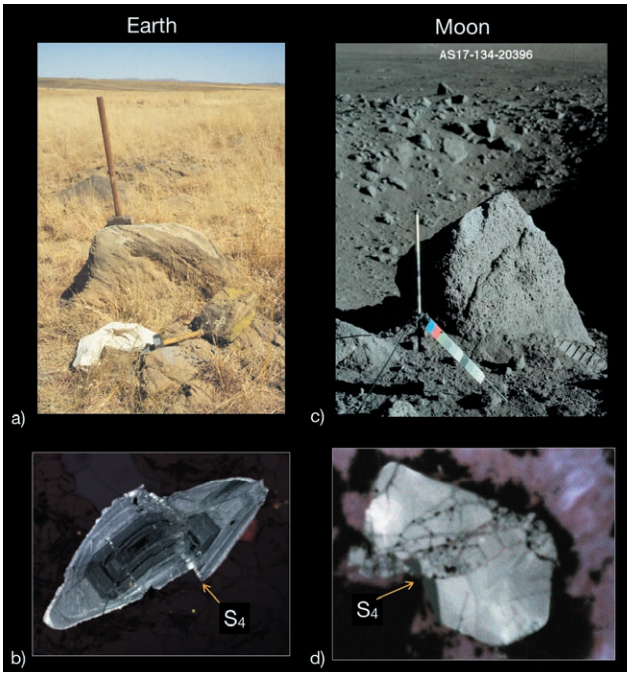

Figure 4. Examples of violent deformation features (S_4) on Earth and the Moon: a) a boulder of Archean (~3 billion year old) crust near the center of the ~250 km wide, 2.020 billion year old Vredefort impact structure of South Africa. b): SEM-CL image of a zircon crystal from this region c) boulder at the edge of Steno Crater (Apollo 17), d) SEM-CL image of a >4 billion year old zircon from near site shown in c).

between fracture sets has been bent by several degrees during shock deformation, a mechanical response in line with Steno's observation for strata which sometimes respond plastically to be "twisted into curves" because of their "tenacity" (above).

S_4 tectonic fracturing and mineral-filled veins

Steno also recognized a style of deformation features such that some strata crack in a brittle fashion to allow fluid pathways for new mineral precipitates. An example of this sequence of S_4 features superimposed on generations of growth features (S_{1a} , S_{1b}) is illustrated here in one of the oldest known fragments of the Earth; a zircon grain from the Archean Jack Hills quartzite from the Yilgarn craton of Western Australia (Fig. 5a). The age, chemistry and microstructure of this grain has been described in detail elsewhere.[88] The central domain (core) has a U-Pb age of 4.38 billion years — a time when the mass of the Moon had already been separated from the proto-Earth and the first water appeared,[89] the latter reminiscent of Steno's first fluids. The first set of growth features (S_{1a}) formed during precipitation from a silica-rich magma in Earth's early continental crust. At modern, average rates of tectonic drift, it is plausible that over the last 4 billion years this core domain has circumnavigated the Earth several times as microscopic continental cargo on a number of early crustal domains. Roughly 3.4 billion years ago, the grain experienced chemical resorption and/or mechanical abrasion which removed S_2 and produced a discontinuity surface, S_3, over which grew a new, metamorphic domain with chemical layering (S_{1b}) discordant to the older core. A tectonic deformation produced S_4 fractures, which reoriented the lattice and its S_{1a}, S_{1b} and S_3 features, prior to their being filled with a combination of new zircon, quartz, and grains of the rare earth phosphate xenotime, the latter as young as 0.8 billion years ago[90](Fig. 5). The mineralogy of the micro-veins, and their younger, intersectional age relationship, are directly in line with Steno's observations of the deformation, veining and growth of secondary minerals.[91] The sequence of production (growth), erosion, deformation, and resumption of growth experienced by this early Earth zircon resulted in a geometric arrangement of features that is very similar to that which Steno described for the crustal strata of Tuscany, illustrating the scale-invariance of Stenonian geochronology (Fig. 5).

S_4 Deformation and renewed production sequence at atomic scales

Stenonian cycles of production and modification can also be seen at the atomic level with electron microscopy at the length scale of Steno's then "imperceptible particles",[92] as illustrated here in a 200 million year old igneous Mars rock that came to Earth as a meteorite (NWA 5298) ~11 million years ago[93] (Fig. 6). The cycle of rapid shock-wave deformation and heating, which such shergottite meteorites generally experience as they are ejected to space following an impact event, leaves a record of mm-scale pockets of melting and glass for-

[88] J. W. Valley et al., in ref. 21.

[89] SA Wilde, JW Valley, WH Peck, CM Graham, Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago. *Nature*, **2001**, *409*, p. 175-178.

[90] Rasmussen B. et al., Metamorphic replacement of mineral inclusions in detrital zircon from Jack Hills, Australia: Implications for the Hadean Earth. *Geology*, **2011**, *39*, p. 1143-1146.

[91] N. Stensen, in ref. 1 (K&M), pp. 629.

[92] N. Stensen, in ref. 1 (K&M), pp. 626.

[93] Moser, D. E. et al., Solving the Martian meteorite age conundrum using micro-baddeleyite and launch-generated zircon. *Nature*, **2013**, *499*, p. 454-457.

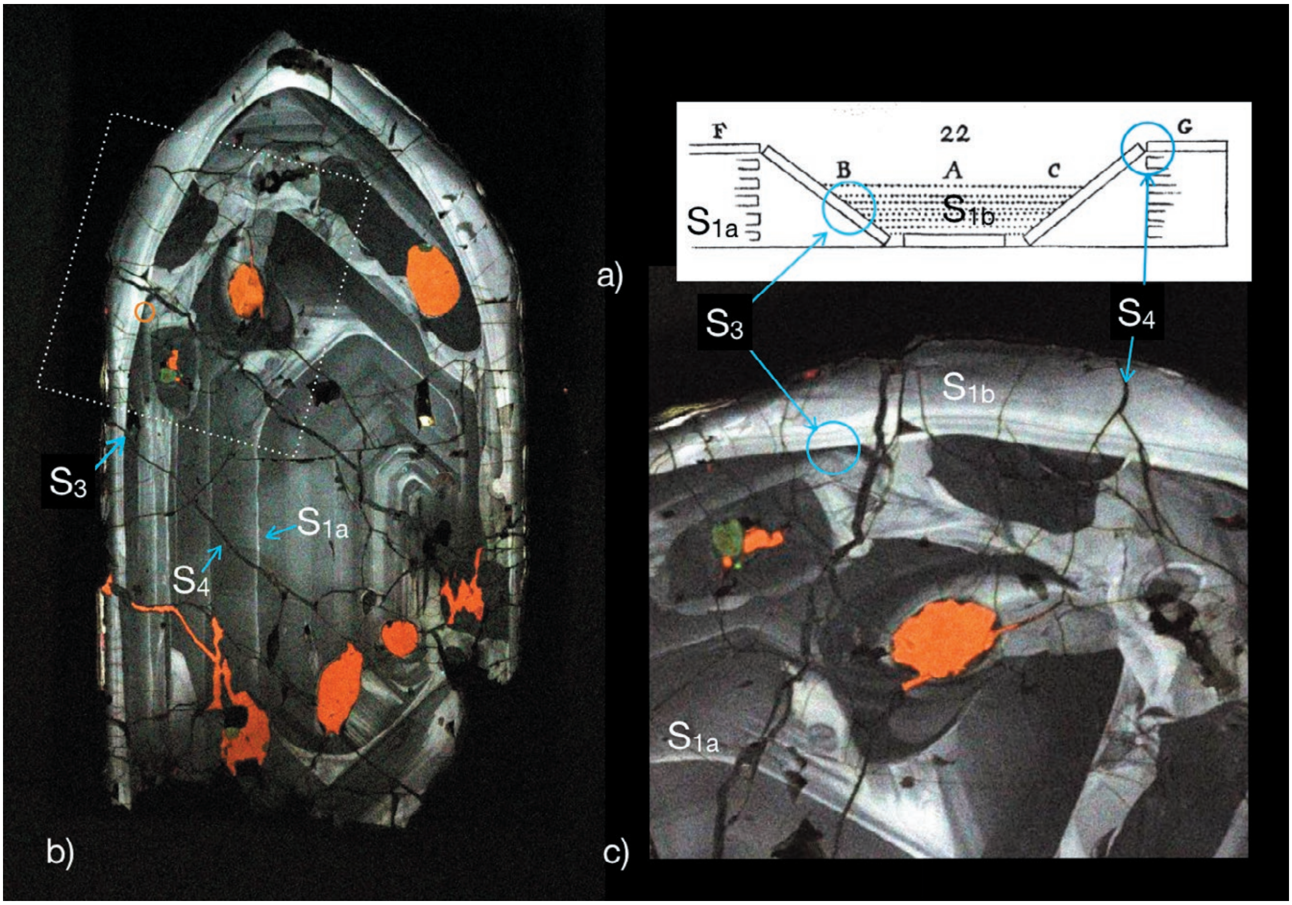

Figure 5. Cyclic growth and deformation; a) Steno's depiction of Tuscan strata (see text for description of annotations), b) SEM -CL image of one of Earth's oldest known mineral grains, zircon with a 4.38 billion year old core. The 3.6 billion year sequence of growth, erosion, deformation and renewed growth features can be seen in higher magnification view of white dotted box, enlarged in c).

mation as well as a suite of microscopic S_4 deformation features within the regular atomic layering of igneous crystals. The heating also triggers short-lived chemical reactions and local growth of minerals, including zircon, during cooling *en route* to space.[94] The resulting continuous and discontinuous patterns among the atomic lattice layers, revealed with electron microscopy, are analogous to the those in strata in Steno's sketches of Tuscan geology (Fig. 6). We can see in Figure 6 that primary atomic layering (S_{1a}) in the Mars mineral baddeleyite (ZrO_2), has been re-oriented and disordered across S_4 surfaces of deformation. A boundary of chemical reaction (S_3) separates the deformed baddeleyite features from younger, atomic layers of undeformed zircon (S_{1b}) at the start of its journey to Earth (Fig 6). This atom-scale Stenonian geochronology, when paired with absolute geochronology methods, allows for back-stripping and dating of a microscopic deformation and chemical erosion sequence developed on a path between planets.[95]

f) *S_5 Chemical diffusion, chronostructures, and Steno's known unknown process*

> *Thus I do not determine whether particles of a natural substance can or cannot undergo change, as its shape can, whether there are or are not minute empty spaces whether in those particles, in addition to the ability to occupy space and the property of hardness, there may not be something else unknown to us; for these statements are not widely accepted, and it is a feeble argument to deny that there is anything else in a certain thing because I do not observe anything else in it.* [96]

[94] ibid.

[95] ibid.

[96] N. Stensen, in ref. 1 (K&M), p. 626.

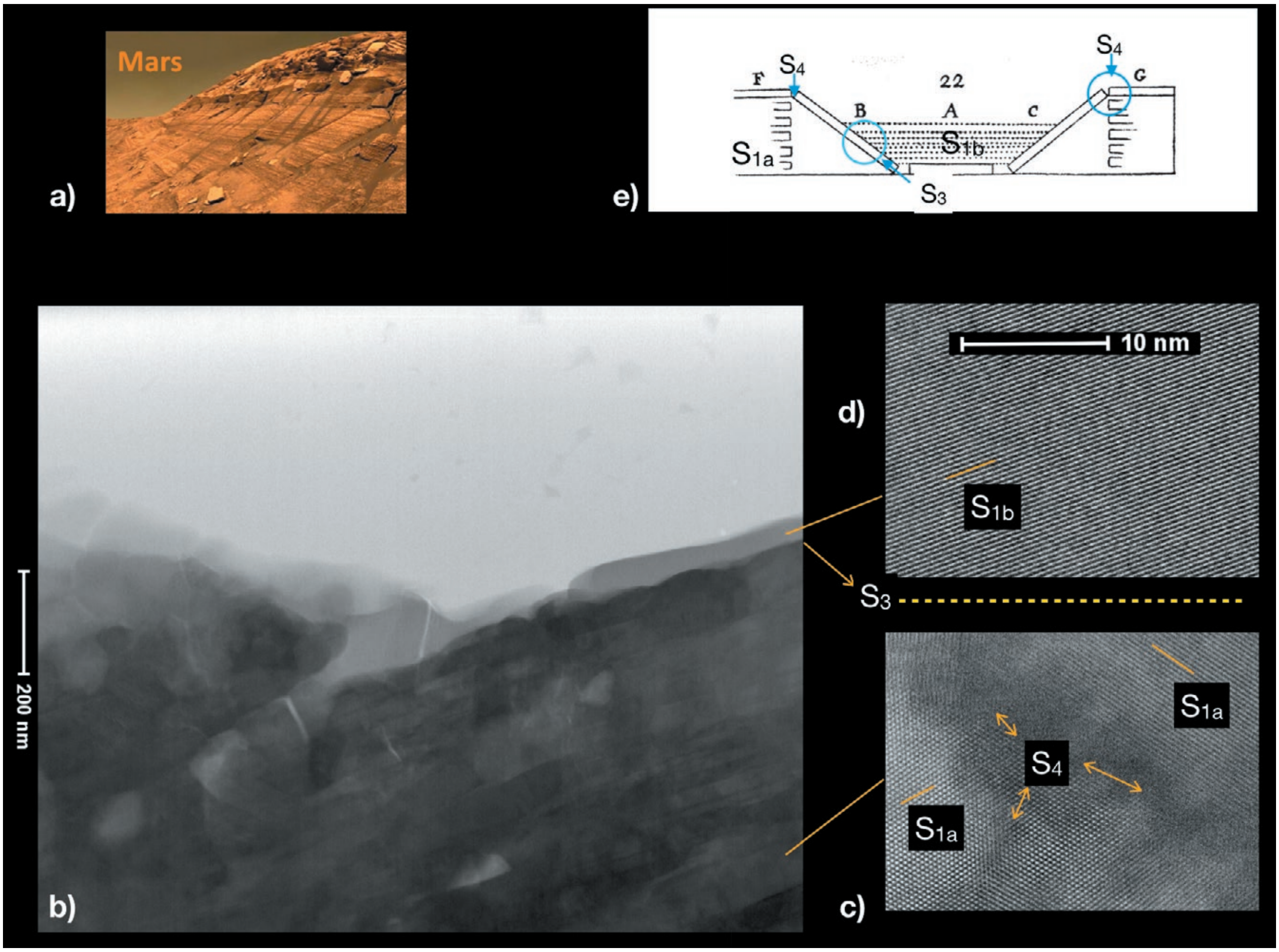

Figure 6. Stenonian time features at atomic scale in a meteorite from Mars; a) a view of Mars strata, Opportunity Rover; b) a STEM image of the shock-deformed atomic layers in baddeleyite (S_{1a}) reacting to undeformed zircon (S_{1b}) in Mars meteorite NWA 5298; Higher magnification STEM images of the disturbed baddeleyite lattice (c), and undeformed zircon lattice (d). e) Steno's Diagram 22.

The fifth class of time features are surfaces of chemical discontinuity created by atomic movements and are distinct from the other four classes in terms of both the strength of connection to Steno and the source of their geometric form. Unlike the other feature classes, Steno did not specifically predict structures at the atomic scale in nature as this was out of observational range. Yet, as can be seen above, he allowed for their existence. They are included here as Stenonian features because Steno's writings in both the *Prodromus* and his later *Prooemium* on the topic of particle (atomic) motion and heat have been previously interpreted as descriptions of diffusion.[97] This feature class differs also in regard to form in that S_5 is not a single, discrete surface but a pair of subparallel surfaces bounding a gradient of chemical change caused by a migration of atoms after solid formation. Steno held the Cartesian view that "A natural body is an aggregate of imperceptible particles",[98] and with recent advances in microscopy, geochronologists can now image and measure the three dimensional distribution of these particles, as either or both elements and isotopes, within minerals.[99] Of particular interest in zircon are the isotopes ^{206}Pb and ^{207}Pb which are the stable decay products of ^{238}U and ^{235}U, respectively. It has recently been found that exposure of zircon to extreme heat in the Earth or in impact craters can cause Pb isotopes to migrate (diffuse) and pile up within the zircon lattice, thereby forming structures *sensu stricto* (Fig. 7). I here introduce the term 'chronostructure' for

[97] J. M. Hansen in ref. 33.

[98] N. Stensen, in ref. 1 (K&M), p. 626.

[99] J. W. Valley et al., in ref. 21.

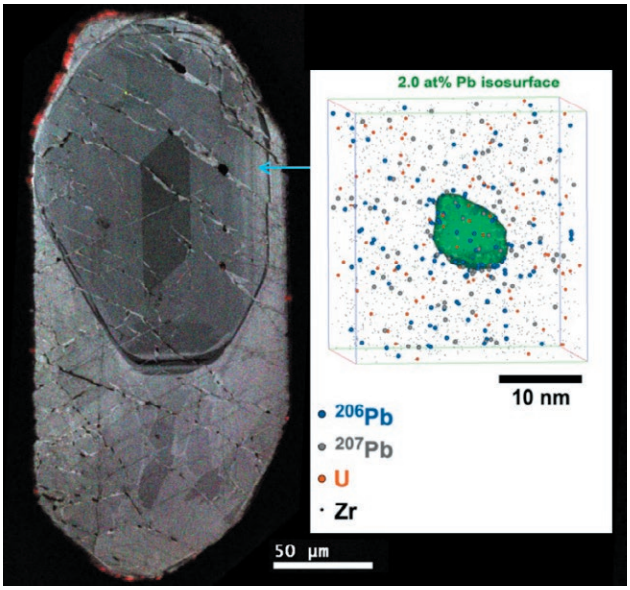

Figure 7. Example of a feature resulting from atomic diffusion (a 'chronostructure'), related to Steno's allusion to such phenomena: Left) A SEM-CL image of a shock -metamorphosed zircon from the Vredefort impact crater zircon, Right) perspective view of a three dimensional atom map of Pb (concentrated above 2%, green surface) and U isotopes imaged in a microscopic needle sampled from this grain (arrow).

this type of S_5 feature as it is a concentration of atoms assembled during an event; an outcome of the universal process of elemental diffusion within or between minerals assisted by either or both deformation and temperature.[100] Zircon presents a special case in that its lattice contains no Pb at the time of zircon crystallization due to energetic exclusion. Thus, each Pb atom seen today is radiogenic and itself an expression of geologic time. Zircon Pb chronostructures reported so far have a variety of shapes but seem to be mostly spheroidal. Examples have been documented from several regions on Earth and the Moon.[101] One example can be seen in a zircon from near the centre of the Vredefort structure in South Africa where, one billion years after its formation, the largest recognized terrestrial impact event caused its S_1 growth zoning to be cross-cut by S_4 shock deformation features (Fig. 7). These contain nanodomains of Pb enriched ~1000x above background levels due to impact-related heating and diffusion. Such chronostructures represent a new type of feature in absolute geochronology.

[100] E. B. Watson, E. F. Baxter, Diffusion in solid-earth Systems. *Earth and Planetary Science Letters*, **2007**, *253*, p. 307-327.
[101] See list of citations in G. A. Arcuri et al., in ref. 40.

4. DISCUSSION

This reconsideration of Steno's time features in minerals in comparison to those for other solids brings to light several themes that illuminate Steno's past and continuing contributions to mineralogy and geochronology. One is his perhaps revolutionary perception of scale invariance among the processes of solid formation in nature; an advance that is implicit in the *Prodromus* but not always recognized. A second theme relates to the source of his observational acuity and the provenance of his scientific philosophy which, together, enabled him to recognize geologic history. Finally, the consistent agreement between Stenonian geochronology with modern microscopy and zircon geochronology opens the door to considering Steno's large, and largely unrecognized, importance in the practice of absolute geochronology.

Steno's fractal features

> *What I demonstrate about Tuscany by induction from many places examined by me, so I confirm for the whole earth from the descriptions of many places set down by various writers.*[102]

It is apparent from Steno's geochronology observations (Table 1) that he saw his results as transcending geography and spatial scale. Steno clearly believed that his findings would have global application, perhaps following the globalist thinking of Descartes which had so impressed him[103]. His view of local processes as a subset of universal operations of the Earth can also be seen as in line with the long philosophic history of macrocosms and microcosms which saw the human body as a facsimile of the workings of an animate Earth.[104] Certainly our examples from zircon geochronology show that Stenonian features are applicable to samples from the Earth and beyond, representing stages in most of the solar system's history. Steno's implicit awareness of the fractal and scale-invariant properties of the visual records in solids, in regard to both space and time, has not been amplified in previous studies of his work, in general, and in mineralogy, in particular. His freedom of mind in respect to physical scale is illustrated in his plate of diagrams[105] wherein he juxtaposes cross sections of cm-scale crystals with two dimensional profiles through a mountainous landscape. Although cross-sectional views

[102] N. Stensen, in ref. 1 (K&M), p. 654.
[103] D. Garber, in ref. 29.
[104] G. P. Conger, *Theories of macrocosms and microcosms in the history of philosophy*. New York, Columbia University Press, **1922**, 142 pp.
[105] N. Stensen, in ref. 1 (K&M), p. 658.

of the Earth were not uncommon in the 17th century,[106] Steno's clear, connection of mineral and land evolution appears to have been without precedent in European natural philosophy. A metaphor for Steno's awareness of fractal scale invariance appears in his earlier writings when praising the scope of the human mind enabled by the Creator: "Finally he will penetrate the inside of the earth and discover the hidden mysteries of the minerals. All these representations respond to a sign as if the macrocosmos laid hidden in the microcosmos".[107] This accurate, fractal vision points to Steno's special abilities and method for natural philosophy.

Steno's methodologic innovation

It is proposed that Steno's achievements in the *Prodromus* were made possible by his innovative pairing of an innate, finely-tuned awareness of the process of visual observation and cognition with a set of Stoic ethical precepts gained earlier in his career, all coming to fruition on the Galilean soils of Florence.

> *Unless the mind is tranquil, it will by no means be free to apply itself to a close examination of facts which can and ought to be closely examined, and unless every least detail is noted in so far as the minuteness of the object or its intricate diversity allows, the pathway to error is downhill and very easy.*[108]

The quality underpinning the classes of scale-invariant time features (Table 1) is that of the cognition of continuity of visual elements in regard to either chemistry or geometric orientation; but, how do we sense continuity? Neuroscience has recently shown that our visual sensory system operates with an inherent "continuity field" such that we have a short-term perceptual bias toward continuity of orientation in geometric forms.[109] The timespan of the continuity field's influence on human perception was measured at ~15 seconds; operating only near the observer's point of focus. It follows that accurate visual cognition of patterns in nature requires time to overcome this natural bias. There is evidence that Steno was very aware from his anatomical training and research that focused, prolonged visual inspection was requisite for accurate science (above). Moreover, he recognized the reward of careful observation in teaching and advancing science in his own time: "Sometimes it takes years to discover that which can then be demonstrated to others in less than an hour".[110] Philosophers who presaged the work of Linnaeus in the next century concentrated on "the external (and particularly the visible) structures of natural objects" [111] and, as mentioned above, Steno's examination of the internal zones of crystals was, in this regard, an innovation. Moreover, upon his arrival in Florence, Steno immediately engaged with the members of the *Accademia del Cimento* which followed in the 'anti-scholastic' Galilean scientific tradition of experimentation and observation, and responded by taking the middle way between scholastics and experimentalists.[112] His primary instrument was human vision with which he interpreted, or abducted,[113] in the language of geo-semiotics,[114] meaning from the landscape. It is proposed that Steno's awareness of the need for self-discipline and time spent in observation was also guided by an awareness of the qualities of observation required if his deductions were to be deemed accurate and recognizable to others.

> *I decided to press with all my might in physics for what Seneca often urges strongly regarding moral precepts; he states that the best moral precepts are those which are in common use, widely accepted, and which are jointly proclaimed by all from every school.*[115]

Perhaps one of Steno's strongest innovations in methodology was to integrate the Galilean experimentalist tradition of Florence with elements of Stoic philosophy as expressed by Seneca (above). Stoic philosophy was respected by the humanists for its systematic approach, and it is perhaps unsurprising to see it appear in Steno's work given his time as a student in Leiden, which is considered to have been the heart of Neo-Stoicism in 16th and 17th century Europe,[116] and where Steno sought out the rich diversity of intellectual thought of the Dutch Golden Century.[117] Steno applies the Stoic (Senecan) tradition in ethics of considering only those sensations all can agree on, and falling within the area of intersection of all scholars' perceptions. Steno's adoption of this aspect of Stoicism to his treat-

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[106] T. Yamada, in ref. 33.
[107] N. Stensen, in ref. 1 (K&M), p. 74.
[108] N. Stensen, in ref. 1 (K&M), p. 112.
[109] J. Fischer, D. Whitney, Serial dependence in visual perception. *Nature Neuroscience*, **2014**, *17*, p. 38-743.
[110] N. Stensen, in ref. 1 (K&M), pp. 128.
[111] W. R. Albury, D. R. Oldroyd, in ref. 27.
[112] J. Bek-Thomsen, in ref. 8.
[113] J. E. H. Smith, Thinking from traces. Nicolas Steno's palaeontology and the method of science, in ref. 8, p. 177-200.
[114] V. R. Baker, Geosemiosis. *GSA Bulletin*, **1999**, *111*, p. 633–645.
[115] N. Stensen, in ref. 1 (K&M), p. 626.
[116] J. Lagrée, Justus Lipsius and neostoicism, in *The Routledge handbook of the Stoic tradition* (Ed. J. Sellars), Taylor & Francis Group.
[117] E. Jorink, *Modus politicus vivendi*. Nicolaus Steno and the Dutch (Swammerdam, Spinoza and Other Friends), 1660–1664, in ref. 8, p. 13-44.

ment of the results of his visual, Galilean experiments in the field allowed him to distill and communicate his uniquely systematic interpretation of natural history.

Steno and modern geochronology

> *To recognize the temporal in the spatial – nobody had done that before Stensen –, from the whole rock to read a dynamic course of time, has since then become and remained the main object of scientific geology.*[118]

It can be argued that Galilean science, and the *Prodromus*, are similarly rooted in the sensation and measurement of time. In 1654, Viviani reported that a youthful Galileo used the period of his heartbeat to recognize the isochronous swings of a lantern through the space beneath the Duomo of Pisa,[119] leading, ultimately, to his famous pendulum studies of the strength and orientations of gravity. One might sense echoes of this approach in the *Prodromus* in which Steno recognized the geometric tracings of time in solids using his highly attuned perception of discontinuity and its, embedded component of time. Steno extended his extraordinary pattern recognition, likely refined through his years of anatomical research, to further place an order on sets of visible features, as in his reconstruction of Tuscan geology; "obvious inequalities in the present surface contain within themselves clear indications of various changes, which I shall review in inverse order, working back from the most recent to the first".[120] In both strata and minerals (e.g. Fig. 1), Steno was thus the first to so methodically order past geologic events based on field experiments, setting the relative geochronology framework which would be employed by Holmes in his proof-of-concept of absolute geochronology more than two centuries later. Stenonian method continues to be vital in geochronology as technical advances enable sampling of ever-smaller volumes and atom-scale observation of elements, isotopes and chronostructures becomes more widely applied; for it is axiomatic that absolute geochronology is dependent on the length-scale of sampling owing to Holmes' principle of the closed chemical system. Conversely, Steno's spatial system of relative geochronology is scale-invariant in respect of both space and time. Steno's classes of visible features of production and modification therefore continue to serve as an independent, intensive, time measurement system for interpreting and checking the accuracy of absolute, extensive, geochronology age measurements to allow us to achieve a more accurate geochronology.

[118] K. von Bülow, in ref. 5.
[119] S. Gattei, *On the life of Galileo: Viviani's historical account and other early biographies*. Princeton University Press, **2019**, p. 440.
[120] N. Stensen, in ref. 1 (K&M), pp. 653.

5. CONCLUSION

Steno's *Prodromus* has been recognized by many scholars as a brilliant, though loosely organized, advance in human observation and perception of records of geologic time in solids. A reconsideration and classification of Steno's writings on processes deduced from solids, and especially atomistic processes in mineral bodies, in terms of visual time features brings to light additional Stenonian advances. Successful comparison of Steno's time features with electron microscopy down to atom scale help demonstrate Steno's implicit appreciation of the fractal, scale-invariant nature of time features. Steno's methodologic advances are also discussed; with the proposal that it was Steno's combination of his awareness of the precision and accuracy of the human visual system with Stoic, and particularly Senecan, precepts in ethics which propelled his remarkable achievements in the rich, Galilean scientific environment of Florence. Finally, it is argued that the intensive quality of Stenonian geochronology causes it to be an invaluable check on the accuracy of extensive, absolute geochronologic age values, thus asserting the modernity of Steno in the geochronology of solids from Earth and beyond.

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