Searching for Modernization—Instruments in the Development of Earth Sciences in Portugal (18th Century)

Isabel Malaquias* and Manuel S. Pinto†

Abstract. In the 1700s the Portuguese government endorsed a mercantilist vision of the kingdom's wealth based in part on an industrialization process relying on mineral resources. The production cycles of gold and diamonds in colonial Brazil were declining and new methods and instruments were needed to revitalize the mining industry. A new enlightened citizen was required and a reform of institutions took place, namely the University of Coimbra. The Lisbon Academy of Sciences and the Ajuda Museum also favoured scientific studies. The quantification spirit of the time helped support the careful practices used in the analyses of minerals, ores and water. Preparing naturalists to travel in Portugal and her colonies was also a task of the institutions, supplemented by prolonged study periods in reputed European centres to get a better education in earth sciences. Books, instruments, mineralogical collections, models and machines were acquired. Several authors wrote about mineralogy, mining, docimasy and metallurgy, while referring to instruments. The circulation of knowledge and instruments came to be one of the important means for modernization, and determined the use of several instruments, such as the barometer and the balance, while the new programme of education was itself a powerful instrument.

Keywords. 18th century, earth sciences, instruments, Portugal

1. Introduction

This paper is about the efforts made in 18th-century Portugal towards the use of new methods in the earth sciences, as part of a program that was carried out aiming at modernizing the country both in industrial and educational terms.

It was a period of some prosperity during which the power of the king was intensified. A better use of the natural resources of Portugal and her colonies in order to reduce the dependence on imports and the improvement of higher education were major concerns of the Crown, intended to emulate other absolute monarchies promoting attention to science and its applications.

*Department of Physics, Universidade de Aveiro, CIDTFF, 3810-193 Aveiro, Portugal. E-mail: imalaquias@ua.pt

†Professor Manuel Serrano Pinto passed away recently on January 15, this article being one of his last scientific contributions.

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It was realized that the modernization of the mining and metallurgical industries and the scientific and technical education of Portuguese naturalists was what the country needed in the middle of the century, when the economy based on mineral resources was declining.

2. Context

The Portuguese 18th-century dominions spread across five continents. Strong connections existed with the Goa territories in India and with Brazil and the African colonies, all of which played an important economic role.

The period of government, from 1750 to 1777, led by the Marquis of Pombal,[1] endorsed a mercantilist vision of Portugal's wealth, partly based on an industrialization process relying on mineral resources, in which Brazil played a decisive role. Brazilian gold and diamonds were the most important mineral resources for Portugal at the time and a great deal of the country's wealth depended on them.

3. A Mercantilist Vision of the Kingdom's Mineral Wealth

Between 1700 and 1735 Brazilian gold production increased slowly, but in the following 50 years it reached fabulous values. However, a turning point was observed by about 1755–1760 (Pinto, 2000). The Government always tried to control the production of gold as well as its subsequent commercial circulation basically because of the revenue derived from taxation.

Concerning diamond production, there was a cycle that started around 1730. The exploitation of the gems from alluvial deposits was open to all from 1730 onwards and carried out on a private basis (with contracts) from 1740 onwards. The creation in 1753 of the *Intendência dos Diamantes*/Diamond Administration that concentrated all the trade of the uncut gems in the hands of the Crown was a tentative measure to combat several problems faced by the industry. The Crown took over in 1771, creating a monopoly—the *Extracção Real*/Royal extraction, which absorbed the *Intendência*—and then production suffered a severe decline resulting in the end of the cycle around 1780 (Machado and Figueirôa, 1999).

So there was a need for improved and diversified exploration and exploitation techniques, not only for gold and diamonds but also for many other minerals of economic value, both in Portugal and in her colonies. Many other European countries faced similar challenges, especially those whose industries depended on the use of metals, such as silver for coinage, as well as industrial minerals and rocks (Laudan, 1987). The Portuguese Crown was the ultimate promoter of the technical development that the country urgently needed in order to revitalize the Portuguese and Brazilian mining industry—not only based on gold and diamond mines, but also on iron, coal, nitre, copper, lead, silver, mercury and other mines.

4. A New Programme of Education

The cultural movement that marked the Portuguese Enlightenment led to the establishment of institutions and enterprises that were of crucial importance to the production, promotion and popularization of technical and scientific knowledge and in this modern spirit the education of a new generation of State naturalists and administrators. Such men, having studied Natural Philosophy at university level, would be able to better exploit the existing resources and conduct scientific expeditions both in Portugal and in her colonies - the so-called philosophical or geognostic travels—as well as searching for new ones.

The expulsion of the Jesuits (1759) ended their long domination of the secondary education system, a change which affected the education system as a whole. After 1759, the secondary and professional studies were extensively reformed (Ferreira, 1998). The foundation of a new school, the *Colégio dos Nobres*, with new curricula, however, proved to be a frustrated and tentative effort (Carvalho, 1959).

The University of Coimbra was reformed in 1772 and conceived as a modern centre of science. New statutes were approved and two new faculties founded: Mathematics and Philosophy, the latter having a 4 year course in natural philosophy. This constituted important evidence of the incorporation of the modern scientific knowledge at the high education level. The guidelines for the philosophical course were in line with Diderot's method of interpreting Nature, namely through observation, reasoning and experimentation: 'Il faut que l'observation de la Nature soit assidue, que la réflexion soit profonde, et que l'expérience soit exacte. On voit rarement ces moyens réunis.' (Diderot, 2005) (The observation of nature should be frequent, reasoning should be intense and experimentation should be accurate. We rarely see these in combination). After studying Rational and Moral Philosophy, students were initiated in the observation and classification of natural facts and phenomena, establishing rational relationships among them, and verifying the plausibility of such combinations by means of experimentation in the disciplines of Natural History, Zoology, Botany and Mineralogy. Experimental Physics and Chemistry were the other disciplines included in the Natural Philosophy course curriculum. Foreign professors came to teach these subjects and also Mathematics, among them was the Paduan Domenico Vandelli (1735–1816) who taught Chemistry and Natural History. Metallurgy was also taught together with Chemistry from 1791 (Ferreira, 1998). The new scientific education was to be both practical and experimental. New premises for practical teaching were constructed, namely a chemistry laboratory, a botanic garden, a physics laboratory with plenty of instruments, a museum of natural history and an astronomical observatory. The library was enlarged with the addition of up-to-date items, and local professors published a few student texts. The members of the teaching staff were required to carry out experimental studies and the statutes threatened penalties to those who still taught 'peripatetically'—loss of rights to teach at the university and the cancellation of any kind of royal support -, whereas those who carried out experimental teaching would receive royal recognition. Collections were purchased and private collectors were encouraged to donate their collections to the university to help support the enlargement of the museum. Fieldwork requiring both recording and some measuring of what was observed and the collecting of samples was carried out both for the benefit of students' practical preparation and to increase the number of specimens in the university's collections. At the same time many students came to Coimbra from Brazil with an interest in Natural History enrolled at the Faculty of Philosophy (Rodrigues, 1990).

After Pombal's leadership and under Queen Maria I sponsorship the Royal Academy of Sciences was instituted in Lisbon in 1779. It adopted Phaedrus's motto *Nisi utile est quod facimus stulta est Gloria* (Unless what we do is useful, our glory is vain) and with this in mind the Portuguese elite promoted applied science via discussion and popularisation. The Academy sponsored studies abroad for some of its members and former Coimbra students, as in the cases of Manuel Ferreira da Camara (ca. 1762–1835), José Bonifácio de Andrada e Silva (1763–1838) and José Fragoso Siqueira (?–1833), who traveled in Europe for several years and studied at Freiberg. They acquired and sent to Portugal models, modern instruments and various pieces of apparatus mostly related to mining and metallurgy and also published books, memoirs and papers on these matters and on mineralogy (Pinto, 1994; Pinto and Malaquias, 2008). The Academy also played a role in teaching natural history (Carvalho, 1981) and established a museum with mineral and other samples collected from different areas of Portugal as well as from her colonies. Several memoirs were published by the institution relating to the characterization of specimens belonging to the animal, vegetal and mineral kingdoms and their importance to the country's economy.

Also integrated in this educative national effort was the development of the so-called Ajuda Museum, created specifically for the royal princes' science education, but which also encouraged scientific studies by its naturalists. Under Vandelli's direction from 1768 onwards, natural history was taught at the museum (Carvalho, 1987) and the acquisition of collections for a future Portuguese public museum began (Brigola, 2000–2001).

It should be pointed out that a little before the Coimbra University reform, a scientific academy (*Academia Scientifica do Rio de Janeiro*) was created in Brazil in 1771 under the patronage of the Viceroy, the Marquis of Lavradio. There were departments of Medicine, Anatomy, Surgery, Natural History, Chemistry and Pharmacy and papers were read and debated at the Academy's meetings. The Academy functioned until 1779 when Lavradio returned to Portugal (Marques, 2005). It was resurrected in 1786 under the name of Rio de Janeiro Literary Society. Some experimental chemical demonstrations were performed there, notably on gases and on the composition of Rio's air.[2]

Vandelli played a leading role in the development of Natural History in Portugal during the 18th century, occupying important posts in both Coimbra and Lisbon (Academy of Sciences and Ajuda Museum). He also wrote quite a lot about Portuguese and Brazilian mineral resources, preparing detailed inventories of such resources and making recommendations about the best ways of prospecting and exploiting them (Vandelli, 1789a–c, 1898a,b). He also kept in touch with many of his former students, receiving from them information and mineral samples (Carvalho, 1987).

Thus various educational goals were on the political agenda, having students, miners and the general public in mind.

5. The Century's Spirit of Quantification

It has been argued that the 18th-century encyclopaedic enterprise inspired quantification and classification in *natural history* studies, as they both possessed similar objectives concerning 'totality, coherence and order.' This being the case, much of the scholarly activity of the late Enlightenment, with its huge flow of information, was in the line of 'inventory and survey for useful purposes' (Broberg, 1990). At the same time, *physics*, while intended as 'experimental philosophy,' was quantifiable through the mathematical laws educed from the experimental results mediated by instruments (Heilbron, 1982). As for *mineralogy*, it encompassed the study of the physical and chemical properties of minerals. *Geognosy* also had some quantitative aspects (chemical composition of rocks, determination of the thickness of strata, etc.). Mineralogy, *metallurgy (docimasy)* and assaying were seen as part of applied chemistry, giving rise to an increased use of the weighing balance. In this way experimental physics could influence chemistry in a programme that was related to a new attitude towards instruments. The impact that mineral resources had on some countries' economies put pressure on and inspired the development of new mineralogical systems.

Careful laboratory practices were implemented in the second half of the 18th-century. Through the use of instruments and their different applications in the context of geological knowledge, mineralogy evolved from classifications being based on the external characters of the minerals, like those deployed by Linnaeus and Werner, to the ones taking into consideration chemical interpretations/composition as introduced by Cronstedt, Bergman and others (Oldroyd, 1973; Newcomb, 2009) and to Romé de l'Isle and Haüy's crystallographic considerations. Nevertheless, that did not mean that the use of 'comparison needles' or touchstones and of other obsolete but convenient techniques were immediately discarded by the assayers. And the weight determination of composition contributed to improved descriptions although in the context of a basically qualitative scheme of classification (Lundgren, 1990). Fieldwork also required more efficient and sophisticated instruments that could make possible the measurements of depths and heights in mines and mountains, strike and dip of strata, trends of linear features, direction of ventilation circuits inside mines, etc. Both field and lab instruments served to investigate the Earth in a scientific manner (Newcomb, 2009).

6. The Circulation of Knowledge and Instruments—The Concept of 'Instrument'

A broad concept of instrument has been adopted in the present paper to illustrate the study of the modernization of earth sciences in 18th-century Portugal. It includes books, memoirs and papers, maps (Oldroyd, 2009), instruments, apparatuses, collections, models, machines and tools; portable labs used for dry and wet analysis; physical and mathematical instruments used for making measurements in the field and in the laboratory. It also covers collections of minerals and rock specimens that were internationally exchanged, which were used as teaching materials for students and miners or displayed in museums and cabinets illustrating the 'great theatre of Nature.' Models, machines and tools, technical devices used in mining, were commonly imported into Portugal, or constructed there and in Brazil from drawings introduced from abroad. Even the basic equipment used in the field by the naturalist for the purposes of making observations, collecting samples and taking notes—e.g. the hammer (Klemun, 2009), auger, chisel, compass, hand-lens, notebook, pocket-knife, etc.—are included in the concept.

As the earth sciences were already a vast field, we need to look at their development, taking into account all these facets of instruments: they were a means to attain the modernity that the Portuguese government had established as its goal. At the same time their circulation was part of a more powerful 'instrument': the Portuguese education programme that emerged following the aforementioned Jesuits' expulsion. The circulation of knowledge and instruments characterized a period when investigators were searching for the best procedures for their construction and use. The barometer and the weighing balance are good examples of such instruments (see below).

7. Circulation of Books, Papers and Other Written Works

Books, memoirs and papers by foreign authors about what was going on abroad, were sometimes translated into Portuguese. Written material by Portuguese-speaking authors was also produced.

Some important books on *mineralogy* circulated both in their original languages and as translations from, among others, authors like Werner (1749–1817), Cronstedt (1722–1765) and Haüy (1743–1822). The Portuguese Vicente Coelho Seabra (ca. 1764–1804) wrote *Elementos de Chimica* that was not only a treatise of chemistry that utilised Lavoisierian theories, but also a compendium of mineralogy, with the description of physical and chemical properties of many minerals, with a classification and the chemical composition of minerals and the mineralogical and chemical composition of several rock types (Seabra 1788/90–1985). This, of course, referred to many lab instruments. In an interesting book published in Lisbon in 1803, about mineral resources (Anonymous, 1803), its Portuguese author listed no less than 20 properties, mostly physical ones, of minerals, mentioned several systems for their classification based on various specific qualities, like Wallerius' (1709–1785), Linnaeus' (1707–1778) and Werner's, and referred very briefly to instruments such as the telescope, the microscope and balance. Various memoirs were published by Portuguese authors, written either in Portuguese or in foreign languages and printed in Portugal or abroad. For example, Andrada e Silva (1763–1838) wrote on Brazilian diamonds and on four new lithium minerals that he discovered while in Scandinavia, and his papers on them were published in London and Paris (Ferreira, 1998). An important memoir on diamonds was also prepared by Vandelli (1898b). In it he mentioned that while he could refer to different authors who had written on those gems, he would write only on what he had observed and analysed about the Brazilian ones, namely their shape, and on their differences from those coming from India (differences in specific gravity, electrical behaviour, and colour).

Mining in the 1700s generally involved a first phase (prospecting, exploration), consisting mainly of observation of the ground looking for promising mineral occurrences in outcrops, taking samples with the auger, hammer or other tools, identifying the matrix of the useful mineral, measuring the physical parameters of veins, strata, etc., using the compass and clinometer, plotting the location of the occurrences on a base map, using the portable laboratory items for chemical and physical tests, etc. The second phase involved detailed studies of the site to assess the richness of the occurrence in terms of useful mineral content and the mineralogy of the rock where it was found, the accessibility of the site and of the mineralized zone, the assessment of the workforce needed to proceed with the exploitation of the resource, and so on. Such studies provided the information necessary to decide whether a mine should be opened and what sort of mining method should be used (opencast, stripping or underground). The exploitation involved the physical extraction of the useful mineral, and its dressing to separate it from unwanted constituents. The last steps were required for metals, metallurgical operations, generally preceded by docimastic studies. The human resources needed to carry out all the operations were huge, as were the numbers of machines, apparatuses and tools (see, for instance, Martins, Brito and Falzoni, 1989). In a manuscript dated 1789, Camara suggested the use of several new machines and apparatuses in the Brazilian mines to increase production and improve the slaves' working conditions. In another manuscript about mining in Transylvania he recommended that cheap rock crushing machines similar to those used there should replace the hand crushing operations that slaves carried out in the Brazilian mines (Camara, 1789, 1796).

Among the many authors who wrote about mining in Brazil, particularly about gold mining, the name of Vandelli stands out because he dealt with practically all the steps from prospecting to docimasy. Curiously the important memoir on diamonds and another one on gold mines (Vandelli, 1898a), probably written between 1783 and 1792 and read at the Academy of Sciences, were published only in 1898, possibly for reasons of secrecy, given the importance of these resources. Referring to the gold tests he pointed out the necessity of improving the assayers' chemical education as the methods performed at the Mint were not kept up to date and several quantifiable losses were observed. Losses in fact occurred all along the line from the moment of gold extraction in the mines until its purification. The methods used and the reagents' quality and properties needed to be modernized for the purpose of gold purification and assaying. The occurrence of mineralized gold with platinum that the assayers in the Portuguese Mint were not recognizing in the ore was, for instance, frequently the cause of considering the fineness of gold to be higher (24 carats) than it was because platinum had a similar behaviour when subject to cupellation and when dissolved in *aqua regia*. Also when comparing methods used to purify and assay the gold at the Mints in Portugal and Brazil with those in England, France or Venice, Vandelli concluded that the losses occurring in Portugal were about 8% higher. In particular Vandelli pointed out the important losses that occurred when gold was treated with *aqua fortis* [sic][3]—'dando o ouro por 22 quilates quando é de 22 e 1/30 ou 1/15 ou 1/21 e às vezes até 23 quilates'/'considering the gold of 22 carats when in fact it corresponds to 22 1/30 or 1/15 or 1/21 and even 23 carats' (Vandelli, 1994). He was following Sage's *Art of Assaying* (1780) on this matter.

The number of works on *metallurgy* and *docimasy* prepared in the 18th-century by Portuguese-speaking authors—André Antonil (1649–1716), Vicente de Seabra, Domenico Vandelli, Ferreira da Camara, Fragoso de Siqueira, José Vieira Couto and Manuel J. Barjona (1758–1831)—is probably much larger than one might expect: 5 books (three published in Vienna and in Dresden and 2 in Coimbra and in Lisbon) and 11 memoirs (4 by Vandelli published in Lisbon) (Pinto and Malaquias, 2008). This publishing activity occurred in the last 15 years of the century. It was certainly the case that the improved metallurgical techniques described in them for the extraction of gold and silver (either native or present in lead ores) from ores were intended to be put into practice in both Brazil and Portugal. Apart from Seabra's text on chemistry, all the others were technical manuals. Early in the century, Antonil, who wrote about two metallurgical methods for silver extraction using lead and mercury, probably based his description on Barba's *Arte de los Metales* (1624). Seabra described several docimastic methods of determining the contents of metals, particularly gold and silver, in ores. Vandelli wrote extensively on the extraction, assaying and purification of the gold present in several types of ore (Vandelli, 1994). Camara wrote about the amalgamation and smelting methods used in gold extraction and a book in French about the metallurgy of silver ores using lead, which was translated into German and commented on by Lampadius (1772–1842), his former professor of metallurgy in Freiberg (Camara, 1795, 1797). Siqueira was the author of a book (in both French and German) about the metallurgical methods for silver in use in Germany (Siqueira, 1800). Barjona wrote (in Latin) the first book on metallurgy ever published in Portugal (*Metallurgiae Elementa*)

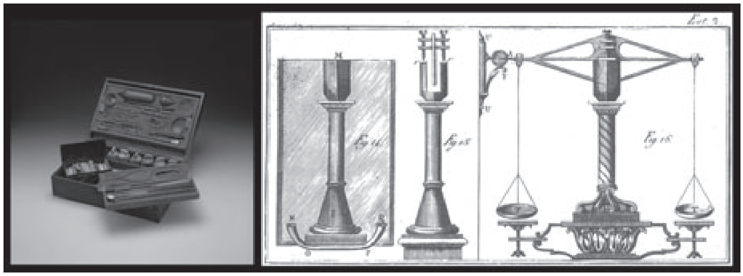

Fig. 1. A portable laboratory for use in the field, including a blowpipe and a Nicholson hydrometer (Photo by I. Malaquias); and a precision balance as illustrated in Barjona's *Metallurgiae Elementa* (1798).

(Barjona, 1798–2001), making use of the new chemical nomenclature of Lavoisier and his co-workers. The instruments and apparatuses needed for docimasy and metallurgy procedures were described and shown in several engravings. Figures 1 and 2 depict examples of such instruments and apparatuses used in the laboratory and in the field. Barjona presents the 'necessary rules' that constitute the science of metallurgy. Concerning docimasy, he mentions the technical rules linking theory to practice and quantification aspects - in each stage of purification making use of an accurate balance. Although mentioning several foreign authors, the book was mainly written as a technical manual without a great number of references.

In the 1700s attempts were made by the Portuguese Government to establish iron works in Portugal (*Ferrarias da Foz do Alge*) (Carvalho, 1953), Angola (*Nova*

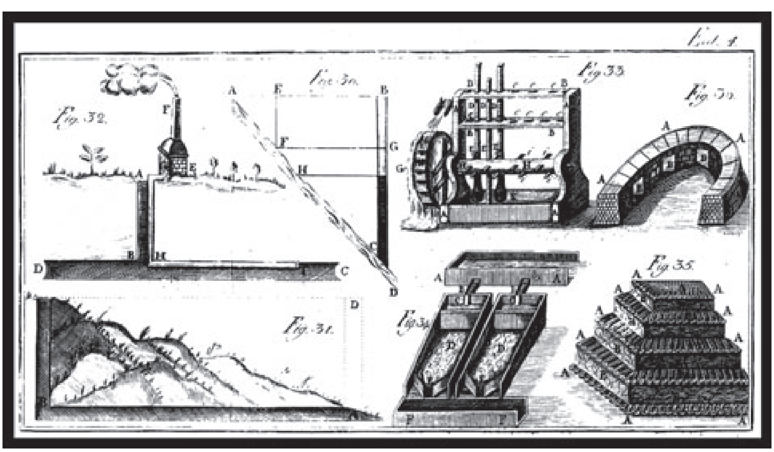

Fig. 2. Drawings of industrial equipment used in the field, according to Barjona's *Metallurgiae Elementa* (1798) (*Fig. 33* - hydraulic stamping mill; *Fig. 34* - washing tables and *Figs. 35–36* equipment for ore calcination).

Oeiras) (Amorim, 2003) and Brazil (*Morro do Pilar*) (Eschwege, 1941), but they were unsuccessful in the short/medium term in the sense that the manufacture of iron did not last for long for various reasons, among them technical ones related to the types of furnace and machinery in use, and the lack of skilled iron founders.

During the 18th-century several pertinent topics of *geology* that were under discussion in Europe were also under discussion in Portugal, namely: (1) volcanism and volcanic rocks (memoirs by Camara, 1794a,b; Vandelli, 1797 and J. S. Feijó (1760–1824), a Brazilian-born naturalist who went to Cape Verde on a geognostic excursion (Ribeiro, 1960); (2) the internal constitution of the globe discussed in books by the physician Ribeiro Sanches (1699–1783) and by the Oratorian Teodoro d'Almeida (1722–1804) (Assunção, 1980); (3) the cause of earthquakes, deserving mention that Ribeiro Sanches performed experiments with Boyle's air pump, which aimed at showing the possibility of explosions occurring in the absence of air, which might cause earthquakes in the Earth's interior (Sanches, 1757).

A clear notion that it was necessary to go 'deep' into the field to get a better knowledge of the natural world implied the sponsorship of *scientific expeditions* (Simon, 1983) by the institutions mentioned above and by the Crown. Such expeditions were performed both in Portugal and the colonies. Among the former the ones conducted by Correia da Serra (1751–1823) (Simões, Carneiro and Diogo, 2003) and among the latter the expedition to the Amazon region led by Alexandre Rodrigues Ferreira (1756–1815) stood out (Carvalho, 1987). Periods abroad were also recommended for studying subjects like chemistry, mineralogy and metallurgy, as well as visits to mines and foundries in several countries as previously mentioned. All that in general led to the preparation of memoirs, books and maps.

The naturalist had to obey a number of careful procedures to observe, register and measure, not forgetting the senses' use to extract as much information as possible from the samples collected. A certain number of specific instruments, either mathematical/physical and chemical ones or even graphic material was established in order that the naturalist could register as many parameters as possible. A new approach was necessary to extract from nature and from the collected samples the information needed, when mediated by the various instruments. In two manuscripts written in 1778 and 1779, Vandelli listed the instruments and tools that naturalists should use in the course of their fieldwork. He introduced the importance of keeping a notebook to record the daily observations and measurements. The compass, maps, notebook, pencils, ink, telescope, hand-lenses, microscope, astronomical instruments for determining the latitude and longitude, thermometer, barometer, watch indicating seconds, balances, hammers, chisels, augers, scientific books, specimens for comparative purposes, chemicals, etc. were of the most importance, as well as the portable labs 'that are in use in England' with all their different components to produce the melting of ores, in small (Figure 1) (Vandelli, 1778, 1779; Cruz, 1976; Carvalho, 1987). With such instruments the naturalist

Fig. 3. Mapa de toda a extenção da Campanha da Princeza ... ca.1799. Da Campanha as Lavras 14 leguas, e das Lavras a S. João 16... (Portugal, 2000).

would be able to determine the metal constituents. Vandelli's instructions were just an example of several instructions to be used by naturalists (Brigola, 2003).

Mineralogical maps, like that shown in Figure 3, presented the location of mines and the routes of how to reach them, apart from rivers, etc. They were kept confidential by the authorities that used them with several purposes, namely the military control of riots in the mines and the transport of gold and diamond consignments from them. The accuracy of such maps was very variable. For instance, many of them did not give the heights of hills, mountains, etc., although in 1728 a book for engineers was published in Lisbon describing the use of topographic techniques and instruments of representation of the ground (Fortes, 1728–1729).

8. Circulation, Production and Replication of Instruments and Apparatuses

Classifying and collecting were important activities that frequently determined the existence of what one might call educational mineral collections functioning as 'mimetic instruments.' Through the careful observation of specimens, naturalists and miners could identify minerals in the field, having become acquainted with 'standard' specimens in collections. Mineralogical collections were acquired abroad and many others came from Portuguese colonies chiefly to enrich the Ajuda Museum, the university and the royal collection.

Copies of models for mining purposes were sent to Portugal from abroad by the travelling naturalists. Many other mathematical and physical instruments were ordered from outside the country where a flourishing scientific instrument market was developing. After 1778, several collections of instruments were produced in England for the Brazilian frontiers to be settled after the Santo Ildefonso Treaty with Spain (Magellan, 1780; Malaquias, 2004). These collections contained several specific instruments necessary for topographic measurements together with the physical (e.g., temperature, magnetic deviation, atmospheric pressure, and time) and astronomic (latitude and longitude) parameters usually taken. Barometers, English quadrants and octants, magnetic needles, thermometers from renowned workshops and instrument makers like Nairne and Blunt, Sisson, Adams, Vulliamy, Grignion, William and Samuel Jones and so on, were shipped to Lisbon and then to Brazil (and other Portuguese colonies). Many others (balances, etc.) stayed in Portugal being ordered by the different institutions concerned with scientific work, namely the University of Coimbra.

9. The Barometer

A trigonometrical survey necessarily involved the measurement of altitudes. Barometers had long been among the instruments of surveyors wanting to represent the surface relief correctly (Taylor, 1966).

In the last quarter of the 18th century, scientists were greatly concerned with the relationships between altitude and the barometer measurements, which were beginning to be understood. Since Torricelli barometers had been improved considerably using different liquids, making glass tubes of constant internal section, changing the reservoir design, the graduating method of the tube and the reading procedure/dispositive. They were also concerned with the comparability between barometers in the same place and under the same pressure. Its portability was not a negligible factor. These different difficulties led to several proposed solutions by theorists and instrument makers, among them the Portuguese J. H. de Magellan (1722–1790) who also introduced modifications to the barometer (Malaquias, 1994). Several types of mountain and portable barometers had already been devised by Jean-André De Luc (1727–1817) and others. The first correct rules ever published for measuring heights by the barometer had been published by him in the *Philosophical Transactions* (1771). His letter to Sir John Pringle (1707–1782) on the 'Barometrical Observations on the Depth of the Mines in the Hartz' had recently been published in the *Philosophical Transactions* (December 1777), the main consideration being the comparability between barometers (for instance a Dollond's and a De Luc's barometer) and the trigonometric method, having found quite reasonable correspondence, after taking into account the different units (French and Hartz's *toise*) and the different methods used. The measurement of heights with the barometer, namely Mont Blanc, enabled the publication by 1776 of tables of the results, reinforcing the barometer's role and increasing reliability as an altimetric instrument.

In 1778, as mentioned above, the courts of Spain and Portugal agreed to demarcate the Brazilian boundaries. That huge enterprise was performed and several collections of instruments were ordered from the best workshops in London, with both governments agreeing on Magellan's expertise to acquire and supervise the construction of the necessary instruments (Malaquias, 1994; Malaquias and Thomaz, 1994). Among them were portable barometers of the best construction. Several surveying groups were in the field, consisting of an astronomer, a naturalist, an engineer and a native interpreter.

Magellan not only supervised the production of the instruments but also added some useful modifications to some of them. A substantial work was his production of detailed memoirs describing the instruments acquired, ways of fixing them by the amateur far away from the specialized workshops and even some historical information on the evolution of some of them, as in the case of the barometer. Writing on this (Magellan, 1779, 1782), he presented the description of his new barometer together with the practical method of its use for taking the heights and depths of mountains and mines, its use at sea and for meteorological purposes. He detailed some operations like boiling the mercury in order to introduce it into the tube avoiding bubbles, the precise observation of the zero and height of the mercury, the conversion decimal tables to French and British units and the way to use them, with examples. The importance of taking the temperatures of the atmosphere and of the mercury in the barometer was pointed out, which implied the use of two thermometers associated with each barometer. At the same time he stressed the importance of comparing the heights of the ground with two barometers. Tables considering mercury expansion, by degree of temperature, according to the barometers' heights were also presented, and calculation rules were provided for deducing the height between places with practical detailed examples, following recent studies performed by Chevalier Shuckburgh (1751–1804) and others.

In his 1779 instructions for the naturalists, Vandelli stressed the need for them to obtain geographical and geological data on altitudes (heights of mountains, inclination of strata and or veins, etc.) which could be achieved either by practical geometry or with the barometer. Vandelli was attentive to this innovation and assumed it to be something to take advantage of, although he did not give details on its use.

10. The Weighing Balance

The analysis of physical and chemical properties of many minerals required the use of analytical balances (Newcomb, 2003). Initially, these were acquired from the best British workshops but later they were replicated in Portugal. A so-called Magellan balance arrived at Coimbra from the William and Samuel Jones workshop and soon after it was replicated by a local artisan José Joaquim de Miranda (Busine and De Smet, 1991). Some balance refinements published in Abbé Rozier's *Journal de Physique* were suggested by Magellan (1781). Their purpose was to improve accuracy by reducing friction and by avoiding errors caused by deformations due to temperature changes. Magellan also presented a method to obtain the best results with the balance and suggested the best way to make the weights. Later in his life, he produced the second English edition of Cronstedt's *Mineralogy* (1788) and included: 'An essay and very accurate method of making original weights' based on the paper published 7 years before in *Journal de Physique* (Magellan, 1788). William Nicholson (1753–1815) writing *The First Principles of Chemistry* gives some information on the comparative weights used in several European countries, including Lisbon. On the balance and measurements, he compares Ramsden's balance made for Dr George Fordyce (1736–1802), Magellan's balance and Ramsden's balance made for the Royal Society, considering their ability 'in general practice to determine weights to five places or better' (Nicholson, 1792).

In his *Metallurgia Elementa* Barjona gave a special place to the precision balance in the context of docimasy/wet chemistry. Curiously similarities can be found between Magellan's balance and what Barjona referred to as 'our balance.' Other proposed modifications to obtain more accurate and precise balances were published later by the Lisbon Academy of Sciences, taking Magellan's comments into consideration.

11. Concluding Remarks

The search for modernization of the earth sciences in 18th-century Portugal involved the use of several instruments, with the new programme of education for the country being itself a powerful 'instrument.' The modernization of geological and other sciences was required by the Portuguese economy especially in relation to the mining industry (and to a certain degree to agriculture) and this was attempted through the use of instruments, here conceived in its broadest sense. As far as the search for precision and quantification was concerned, the path to modernization was included in a wide context of application both in the laboratory (chemical and mineralogical methods) and in the field (surveying). In education, scientific expeditions, visits and studies abroad were essential, as well as the new courses in Portugal with updated curricula.

In all cases, circulation of knowledge was occurring and in this process the instruments were 'actors,' with their manufacture increasing and developing during the period. An example was the barometer, used extensively in Brazil. But we should not forget the new institutions, the new experimental education, the extensive use of physical and chemical instruments, what was written in technical and scientific books and memoirs, and how the Academy of Sciences, the Ajuda Museum and the Coimbra University libraries and collections were enlarged. By the end of the century, the number of graduated students in Natural Philosophy, many of them Brazilian-born, had increased and as Vandelli projected they were occupying several administration positions and could play a part in defending the importance of the Brazilian mineral resources in preserving Portugal's independence and economic strength.

It is not easy to follow how quick was the appropriation of the chemical modernization at the Mints in Portugal and Brazil. Vandelli knew and most probably taught about it at the university and many of his students were also able to discuss and publish on the subject as discussed above. Although the publication of *Metallurgiae Elementa* (1798) occurred at the advent of the creation of a discipline of Metallurgy (1801) in Lisbon, the subject had been taught at the university (Chemistry and Metallurgy) and there were several professors and demonstrators in charge of the subject. The creation of a Metallurgy discipline recognised that those subjects were improving and that it was an important and specific matter to be taught.

Despite all this activity and proposals, neither industrial foundries for gold and silver nor an iron industry worthy of the name were established in Portugal or Brazil. It was only in the following century that some of these proposals became a reality.

The gap between scientific knowledge and the practical technical expertise probably did not facilitate the appropriation process immediately during the last years of 18th century. From a scientific point of view, underground and other mining techniques needed to be adopted in order to overcome the decline of the mining industry. However, mine owners who had the exploitation rights, never wanted to take that measure, because of damage to their agricultural lands and because the slaves refused to work underground, due to rock falls and fear of working in the dark (Pinto, 2000).

By the end of 18th century, the existing political context, with an absolutist monarchy, the threat of the French invasions followed by the moving of the Court to Brazil (1808) created tensions. Also many of the experts who were working for the Crown questioned the 'dominance of the central metropolitan power itself' (Furtado, 2010). In this context, it is interesting to point out that scientific experts were involved to some extent in Brazil's process of independence.

There was an enormous effort towards modernization in Portugal and there were some achievements. The mission was vast and worthy, but it has not been highlighted and accomplished to the extent that one might expect.

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NOTES

1. Sebastião José de Carvalho e Melo, first Count of Oeiras and Marquis of Pombal (1699–1782).
2. Pinto *et al*. (2005, 2006).
3. 'He necessario muita cautela no Ensayo do Ouro com a Agoa Forte: advertindo o célebre Brandt, com as esperiencias feitas na prezença de ElRey da Suesia, e da Academia, que a Agoa forte dissolve alguma porção de ouro.// Schaeffer, Bergam[an], e Mr. Sage no seu Tratado da Arte de Ensayar o ouro e a prata, confirmão esta mesma esperiencia; porem Mr. Macquer, Cadet, Lavoisier, Baumé, Cornet, e Bertholet, consultados pelo Ministro da Fazenda de França asseguraõ que ainda, que o dito acido algumas vezes dissolva hua levissima porção de ouro, isso pode não ser prejudicial nas cazas da moeda, porque as circunstancias necessarias para esta dissolução são estranhas, e ignoradas nos ensajos, que se fazem nas ditas cazas. (...)'/ It is necessary great caution when essaying gold with *aqua fortis*: the famous Brandt's warning with the experiments made in the presence of His Royal Majesty of Sweden and the Academy, is that *aqua fortis* dissolves some portion of gold. // Schaeffer, Bergam[an], and Mr. Sage in his *L'Art d'essayer l'or et l'argent*, confirm this same experiment; however Mr. Macquer, Cadet, Lavoisier, Baumé, Cornet, and Bertholet consulted by the French Minister of Finance assure that even if the said acid dissolves sometimes a very small portion of gold that cannot be harmful to the mints as the necessary circumstances to that dissolution are strange, and ignored in the assays made there...' (Vandelli, 1898a).

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