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From Alchemy Through Geochemistry to Cosmochemistry

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Motto : "The history of geochemistry has not been written so far,
Even the materials for it have not been collected yet."

(A. E. Fersman)

INTRODUCTION

The 100th anniversary of A. E. Fersman's birth furnishes a good opportunity to outline the history of geochemistry, one of the sciences studying the Earth's material composition.

Care has been taken to put the individual scientists and the achievements discussed into the context of social, economic and technical development. In fact, on several occasions, what seemed to be brilliant ideas remained unproductive and only of historical interest, having appeared before their time and having been technically unworkable. But in some other cases scientific development was given extraordinary impetus by essential improvements of technical facilities and/or changes in the social and economic background.

1. PRESCIENTIFIC ROOTS—PHILOSOPHY AND ALCHEMY (FROM ANTIQUITY THROUGH TO THE END OF THE 16TH CENTURY)

However interesting they might be, early Chinese and Indian speculations are disregarded here as having no direct impact on the development of geochemistry, a science born in Europe.

It is remarkable that early atomistic concepts (Democritus's for instance) had no influence either. Aristotle's philosophy dominated all minds in the Mediterranean civilization for almost two millennia.

1.1. Anitiquity

Aristotle of Stagira (384—322 B. C.) said substance consisted of two principles: matter and form, producing four elements (earth, water, air and fire) and endowed with four fundamental properties (warm, cold, dry, wet). Combinations of these would explain all the variety of natural bodies.

Accordingly, transformation of materials (e.g. metals) into each other was considered possible *a priori*. This was the concept that provided the theoretical basis for the development of alchemy, directed, first and foremost to the artificial production of gold, the noblest of all metals, from other less noble ones.

Bolos of Mendes (Egypt, 2nd century B. C.) is considered to have been the founder of alchemy. Much later, about 300 A. D. Zosimos of Panapolis compiled a treatise consisting of 28 "books."

At that time, research went in two distinct directions : hermetic-esoteric philosophy (very hard to decipher and interpret), and pragmatic experimentation which resulted in a step-by-step invention of fundamental laboratory technique.

1.2. Middle Ages

1.2.1. Arabic Science (s.l.). From the 7th century onwards, the subsequent Arabic-speaking Moslem empires (expanding from the Near East as far as Central Asia and Spain, respectively) provided far better possibilities for the development of science than did Europe of the "Dark Ages" after the collapse of the Roman Empire.

Alchemy (the very name of which is also Arabic) was largely elaborated on the basis of translations of Greek and Egyptian works.

In this context, the name of Jabir Ibn Hajjan (8—9 century), known in medieval Europe as "Geber," should be mentioned first.

Abu Reichan Al-Biruni's (972—1048) *Kitab-il Jawahirfi'l Jawahir* (*Book of Precious Stones in Precious Stones*) is a treatise on mineralogy, much more advanced than the classification forwarded by Theophrastos, a disciple of Aristotle.

Abu Ali Ibn-Sina (980—1037), known in medieval Europe as Avicenna, made important critical remarks on the alchemistic approach, proposing a clear distinction between "essential" and "non-essential" properties of matter.

1.2.2. European Alchemy started with translations from the Arabic. In most cases, the authorship of some often-quoted treatises is somewhat doubtful. Nevertheless, a few names are worth mentioning.

They include Albert von Bollstädt (1193—1280) surnamed Albertus Magnus ; Roger Bacon (1214—1294), and Raymundus Lullus (1235—1315).

Solid bodies were considered to consist of mercury and sulphur. Basilius

Valentinus assumed a third component called salt. Of course, mercury, sulphur and salt were not understood in the present-day sense of these terms.

Individual metals were supposed to be in connection with, and under the influence of, individual celestial bodies (planets). Accordingly, they were given corresponding astronomic symbols. By a stretch of imagination these ideas can be recognized as the prescientific roots of cosmochemistry.

1.3. Renaissance

The early stage of capitalistic development within the feudal society of Europe, involving both essential progress in technology and new ways of (relatively) free thinking, led to new approaches.

Bombast von Hohenheim (1493—1541), better known as Paracelsus, left the rather swampy fields of alchemy to create iatrochemistry (medical chemistry) destined to produce efficient drugs.

Georg Bauer (1490—1555), writing under the name of Agricola, summed up in his monumental work *De re metallica* the knowledge won by centuries-old mining experience in Central Europe. He came forward with some strikingly modern ideas, e.g. that about the ore-generating role of warm water solutions circulating in the "mountains," or rocks.

Nevertheless, alchemy persisted for a long time, till the end of the 18th century, paving the road towards modern chemistry, but also hampering its becoming a science.

2. PHILOSOPHICAL SPECULATIONS AND THE BIRTH OF GEOLOGY AND CHEMISTRY AS SCIENCE (17TH—18TH CENTURIES)

It was at that time that having dropped the Aristotelian tradition, scholars for the first time began seriously to study the material constitution of the Earth.

On the philosophical side we are deeply indebted to R. Descartes (1596—1650) for his two works *Le discours sur la méthode* (1637) and *Principia philosophiae* (1644). Discarding earlier ideas he firmly declared that the Earth, the Sun and other celestial bodies are made up of the same matter. Moreover, he produced the first figure of concentric "shells" of the Earth, with high-temperature solar matter at the centre. Accordingly, he can be regarded as an early forerunner of plutonism.

"Geology" in the modern sense appears, possibly for the first time, in the title of *Geologica norvegica* by M. P. Escholt in 1657.

However, it was N. Steensen (Steno) (1638—1686), with his *Prodromus de solido intra solidum naturaliter contento* (*Treatise on the Solid Bodies Contained by Other Solid Ones*), published in 1669 as the first textbook of geology, who can be called "the first geologist."

A. Kircher (1601—1680), a Jesuit with personal experience in cave exploration, in the observation of volcanic eruption and in the telescopic study of the Sun, published his admirable *Mundus subterraneus* (*The Subterranean World*) in 1664. This work is an amazing intellectual composition of Aristotelian views, strikingly daring novel ideas and painstakingly described facts observed everywhere his correspondence could reach. (The method of questionnaires had been used, relying upon the extraordinary facilities provided by the global network of the Jesuit order.) Kircher severely criticized the futile alchemistic approach and suggested ideas about various mineralizing solutions heated in the Earth's interior by "prophylacia" (roughly corresponding to magma chambers).

G. W. Leibnitz (1646—1716) in the *Abstract* (published in 1693) of his *Protogea* arrived at the crucial distinction between fire-born (igneous) and water-born (sedimentary) rocks. Would his distinction have been taken into consideration by ensuing generations, the long-lasting war between plutonists and neptunists which cost a lot of energy and trouble might have been avoided.

R. Boyle (1627—1691), in the England of the industrial revolution, facilitated the birth of scientific chemistry by founding modern atomisms. At about that time, R. Boskovic (1711—1785) in Dalmatia conceived a peculiar brand of energetic atomisms, starting from purely philosophical considerations, which could not be appreciated in pre-Einsteinian times.

In the chronological order, we now arrive at M. V. Lomonosov (1711—1765), a unique phenomenon in the history of geological sciences. If his ingenious ideas about the migration of elements and—as one would put it now—the geochemical criteria of ore prospecting, had been appreciated, scientific geochemistry could have been born a century earlier. However, the unfavourable socio-economic conditions prevailing in Russia doomed him to solitariness as a pioneer of modern thought, to be rediscovered and duly appreciated only a century later.

It was in France, at the time of the intellectual and social movement of the Enlightenment which relied upon the industrial revolution started in England and led to the bourgeois French Revolution, that modern chemistry was born, along with some early approaches to geochemistry.

G. F. Ruelle (1703—1770) undoubtedly contributed enormously to the expansion and popularization of chemical knowledge. But it is A. L. Lavoisier (1743—1794) who is considered to be the Father of Chemistry. (His highly promising career was literally cut short by the guillotine.) His work on the chemistry of water and on the physiology of respiration prepared the way to some geochemical approaches. Leclerque de Buffon (1707—1788) also touched in his works on several problems that can be regarded as "geochemical" ones.

In England, J. H. Davy (1778—1829) was already intrigued by differences in the occurrence of chemical elements in the Earth's crust. At his time, however, this kind of research, constituting an integral part of systematic chemistry, did not develop into a particular discipline. We can speak at best of beginnings of geochemistry.

J. Reil (1759—1813) and A. von Humboldt (1769—1859) deserve particular attention for having pointed out the importance of studying the chemical composition of living organisms. Von Humboldt even emphasized the interrelation of organisms with the environment and their impact upon natural processes.

In geology (or better perhaps still "geognosy") only A. G. Werner (1749—1817) elaborated the theory of neptunism with all its consequences, eclipsing J. Hutton's (1726—1797) plutonism for a long time. The confrontation between those two theories lasted for several decades, wanting incredible amounts of intellectual energy.

In 1798 M. V. Severgin coined the term "mineral association," implying geochemical considerations. His ideas, however, remained unknown outside Russia.

At the turn of the 18th and 19th centuries, everything seemed to be ready for geochemistry to emerge. However, as Verbadsky correctly pointed out, that opportunity was missed, and for several reasons. The notions of atom, element, crystal and mineral were still rather vague and ill-defined. No appropriate analytical technique existed.

Moreover, chemistry and geology developed along different lines. The latter of the two got involved in the struggle between neptunism and plutonism, and somewhat later, geologists focused upon the elaboration of stratigraphy (based upon W. Smith's pioneering work). Even later, the conflict of uniformitarianism and catastrophism (much more sophisticated than is usually thought, as shown in a fascinating way by R. Hooykaas) also contributed to the interest moving away from geochemical problems, and towards evolutionary paleontology.

3. FROM CHEMICAL GEOLOGY TO GEOCHEMISTRY (19TH CENTURY)

In spite of the above-mentioned currents, the chemical approach kept invading geology along three lines.

3.1. Collecting Evidence of the Material Unity of the Universe

In this context the name of E. F. Chladni (1756—1827), one of the outstanding pioneers of meteorochemistry, should be mentioned. As far as the meteorites were concerned, chemical identity and mineralogical differences were established in comparison with terrestrial materials.

J. Liebig (1803—1873) developed the chemistry of living organisms, starting to clear up their role in the natural circulation of elements (*K* and *P* cycles), thus putting into practice the ideas conceived by Reil and A. v. Humboldt, as mentioned before.

3.2. Early Data and Ideas on the Chemistry of the Geospheres

In this field, I. J. Berzelius (1779—1848) should be mentioned first, without entering into details.

So far as we know, Chr. Fr. Schönbein (1799—1869) was the first to use the term "geochemistry," in 1838 (according to other sources, already in 1832).

But "chemical geology" was a much more widely used term e.g. *Lehrbuch der physikalischen und chemischen Geologie* (published 1847—1854), by C. Bischoff (1792—1870).

Geochemical processes connected with volcanism were discussed by Elie de Beaumont (1798—1874) in his *Emanations volcaniques* (1846).

J. F. A. Breithaupt (1791—1873) wrote a book called *Paragenesis der Mineralien* (1849). The concept of mineral paragenesis, corresponding to Severgin's "mineral association," involved the recognition of geochemical processes controlled by geochemical laws. J. H.van't Hoff (1852—1911), who applied physical chemistry to mineral genesis, contributed a lot to the elementary understanding of these processes.

During that stage, the geochemical cycles of elements were studied in some detail. J. A. B. Dumas (1800—1884), for instance, contributed considerably to the understanding of the cycles of oxygen and carbon.

S. Arrhenius (1859—1927) discussed the geological role of CO_2, thus laying foundations for historical geochemistry, dealing with the evolution of the chemical composition of the geospheres. By that time, two indispensable prerequisites for the birth of modern geochemistry had been available. Emission spectrography (1860), invented by G. Kirchhoff (1824—1887) and R. Bunsen (1811—1899) provided a highly efficient analytical tool to would-be geochemists.

The periodic flaw of elements elaborated by D. I. Mendeleev (1834—1907) proved invaluable for the understanding of the behaviour of chemical elements in function of their atomic structure.

3.3. Collecting Experimental Data on Geochemistry

In Russia, V. V. Dokuchaev (1846—1903) created modern pedology or soil science, including soil chemistry as an important branch. Chemical processes going on in the soil, the site of intense interaction of the lithosphere, hydrosphere, atmosphere and biosphere, represent a problem of great importance in geochemistry even today.

In the USA, F. W. Clarke (1847—1931) was collecting analytical data on the Earth's crust, from 1882 on, with incredible patience and assiduity. His monumental work, a veritable "Old Testament" of geochemistry, entitled *The Data of Geochemistry,* was first published in 1908. To his honour, the average concentration values of elements in the Earth's crust are called "clarks." Curiously enough, Clarke was interested in alchemy in his early years, returning to the topic towards the end of his life.

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Towards the end of the 19th century, modern atomic theory was revolutionized by the discovery of radioactivity (A. H. Becquerel, P. and M. Curie). "Atom" and "chemical element" were considered to be identical, but atoms were no more considered as indivisible and immutable. The way stood open for some sort of "modern alchemy" dealing with the transformation of elements. A few years later, the "solar system" model of the atom, proposed by N. Bohr, opened new vistas to the understanding of the properties and behaviour of elements. Positive and negative ions turned out to be just as important for geochemistry as the neutral atoms themselves.

At the same time, with the rapid advance of astrophysics (studying electromagnetic spectra of various celestial bodies) it became obvious that geochemistry was but a special case of astrochemistry or cosmochemistry.

With progress in the understanding of the geodynamic processes, it turned out that in most of the geological processes only the crust is involved. Accordingly, geochemistry should concentrate its efforts primarily on the investigation of the composition and processes of the lithosphere.

4. BOOM OF THEORETICAL AND APPLIED GEOCHEMISTRY (1900—1945)

This—maybe the most essential—stage in the development of geochemistry is closely linked up with three outstanding personalities, viz. V. I. Vernadsky, A. E. Fersman and V. M. Goldschmidt.

If Clarke's *Data of Geochemistry* is considered the "Old Testament" of geochemistry, the *oeuvre* of this trio can arguably be regarded as its "New Testament."

That is why the year of the death of the former two, 1945, has been chosen as the closing date of this decisive stage.

4.1. Laying Foundations for Theory

The theoretical elaboration of geochemistry was carried out by V. I. Vernadsky (1863—1945) in his work of enormous impact : *La Geochimie* (1924). A disciple of Dokuchaev, he created also a new interdisciplinary science—biogeochemistry, by writing *La Biosphère* (1929).

A scientist of equal stature, A. E. Fersman (1883—1945), as K. Rankama and Th. G. Sahama pointed out in 1959, "sought the ultimate causes of the distribution of elements in their atomic structure and studied their distribution in the Universe, thus incorporating geochemistry with cosmochemistry." Fersman was the first to read an independent university course on geochemistry (Moscow 1912). He attributed a fundamental role to geochemistry in the revolutionary development of a new world concept, because "geochemistry is speaking the universal language of atoms." This would lead to the "chemicization of geological thinking," including the geochemical approach to historical geology, tectonics, and even paleontology (indeed, this is becoming true in our days). According to Fersman, geochemistry should be capable of doing a quantitative forecast of the local distribution and accumulation of elements, relying upon universal laws and regional regularities. This direct challenge to apply geochemistry in mineral exploration was brilliantly met by both himself and his innumerable disciples. Applied geochemistry got an excellent opportunity to develop rapidly with the newly born Soviet State, which was badly in need of mineral resources which could be explored over a vast territory of two continents within a short time and with a minimum of expenses.

4.2. Application of Physical Chemistry and Crystal Chemistry

By this point it is no longer possible to enumerate the names or discuss achievements of all those who contributed to the rapid development of geochemistry.

W. Nernst, G. N. Lewis and J. H. L. Vogt, should be considered only as examples, and the application of the principle of the minimum of free energy should be mentioned.

V. M. Goldschmidt (1884—1947), who worked in Oslo and Göttingen, is one of the giants. He elaborated the laws of element distribution (*Verteilungsgesetze*) based upon ionic radii and ionic potentials, established the geochemical classification or grouping of elements, studied numerous trace elements, was the first to investigate coal ash, to carry out studies in sedimentary geochemistry, etc.

Silicate equlibria, essential for the understanding of igneous processes, were studied at the Geophysical Laboratory of the Carnegie Institute in Washington, D.C.

4.3. Analytical Data and Interpretation

Side by side with Clarke, H. S. Washington (1867—1934) contributed essentially to the data base of geochemistry.

The invention of X-ray spectrometric techniques by A. Hadding (1922) provided a new and very useful analytical tool.

Beside the investigation of major and minor elements, special emphasis was laid upon the study of the rarest ones. By way of example, the work of Hungarian-born Noble Prize Winner Gy. Hevesy (1885—1966) on hafnium should be mentioned in this connection.

5. DIFFERENTIATION AND UNIVERSALIZATION (PARTLY OVERLAPPING WITH THE PREVIOUS STAGE)

Accelerated progress inevitably resulted in differentiation within the science of geochemistry on the one hand, and in interdisciplinary contacts of geochemistry with other sciences, on the other.

At that time, the main research centres or schools of geochemistry were Moscow—Leningrad, Oslo—Göttingen, Freiberg, and Washington. It is easy to recognize that these had developed on the solid basis of an old tradition in science and mining of the countries concerned.

The main directions of research can be indicated as follows (no attempt is made to connect them with names, in lack of sufficient historical perspective. It would be as impossible to enumerate all the prominent geochemists of our time as to characterize the trees of a forest one by one) :

— Geochemical cycles of individual elements,
— Radiogeochemistry,
— Radioactive dating by means of isotope geochemistry,
— Paleophysiology,
— Biogeochemistry,
— Regional or landscape geochemistry,
— Sedimentary facies geochemistry,
— Geochemical petrology,
— Geoenergetics,
— Organic geochemistry,
— Geochemical mapping and geochemistry applied to mineral exploration,
— Geochemical foundation of global tectonics.

Of course, nowadays geochemical research is no more the privilege of a few countries. It is taught at the universities all over the world. An international journal on geochemistry entitled *Geochimica et Cosmochimica Acta* was started in 1951. This title alone shows that these two disciplines are considered inseparable.

It should be permitted the author of this paper to devote a few sentences to the development of geochemistry in his own country. In Hungary, M. Vendel (1886—1977) and E. Szádeczky-Kardoss (1903—) are regarded as pioneers of modern geochemistry. The former contributed essentially to the knowledge of the laws of element distribution. E. Szádeczky-Kardoss, beside having produced the first textbook on geochemistry in Hungarian (1955) improved the geochemical grouping of elements and endeavoured to elaborate an all-comprising theory of the Universe, adopting for it the term "Geonomy" (1974). Of course, it would be far beyond the scope of this paper to deal with this topic. It is only to point out that beside increasing divergence there is also a tendency towards unification and universalization in Fersman's "world concept" sense.

6. GEOCHEMISTRY BEYOND THE EARTH

Extra-terrestrial geochemistry, anticipated by meteorochemy and astrophysics in the last century, became a handfast reality in the course of space research, from the 1960s on.

Up to now, it has been restricted to the geochemical research of the Moon, Mars and Venus, carried out in different ways and at different scales.

6.1. Geochemistry of the Moon ("Selenochemistry")

— Automatic analysis of lunar soil (Surveyor missions, etc.),
— Automatic sampling of lunar soil investigated in laboratories on the Earth (both US and Soviet programmes),
— Personal sampling carried out by astronauts of the Apollo programme, including the first professional geologist to step on the Moon (H. Schmitt, member of the Apollo-17 crew—Dec. 11, 1972).

K/U, Rb-Sr, U Th-Pb and other studies of the lunar samples changed our ideas about the origin and development of the Moon considerably.

6.2. Geochemistry of Mars ("Areochemistry")

Martian geochemistry is only beginning to develop. Earlier analyses of Martian atmosphere accomplished by Mariner spacecrafts were followed by automated soil analyses carried out by Viking-1 and Viking-2 in 1976. The question of life on Mars, however, has yet to be answered.

6.3. Geochemistry of Venus ("Aphroditochemistry")

Both Soviet (Venera) and American spacecrafts have furnished data on the atmosphere of the "sister planet" of Earth. Starting from the chemical composition and "*p*—*t*" conditions of the Veneran troposphere, V. L. Barsukov et al. in Moscow used computer simulation programmes to determine the probable mineral composition of the weathering crust of basaltic and rhyolitic rocks, assumed to make up the solid surface of Venus.

International cooperation is fostered by the activity of COSPAR (International Commission on Space Research), started in 1958.

Along with the investigation of the Moon and the terrestrial planets, theoretical generalizations have also been undertaken. Some titles speak for themselves :

A. E. Ringwood (1966) : *Chemical Evolution of the Terrestrial Planets*;
Y. A. Surkov, G. A. Fedoseev (1974) : *Radioactivity of the Moon, Planets and Meteorites* ;
J. S. Lewis (1974) : *Chemistry of the Solar System* ;
E. Anders (1980) : *Composition of the Terrestrial Planets.*

In space, geochemistry is expanding towards the Galilean moons of Jupiter and to the giant planets themselves on one side, and Mercury on the other.

It was an event of great importance that a joint Soviet-American Conference was held on the Cosmochemistry of the Moon and Planets in 1974. If its forces are united, human mind is bound by the Universe only. It is only to be hoped that peaceful scientific cooperation will continue both on Earth and in outer space.

In this way, the imminent danger of an eventual "post-scientific" stage of geochemistry, most likely reduced to the use of primitive stone tools and suffering of the effects of elevated radioactivity, can and should be avoided.

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