strain
An International Journal for Experimental Mechanics

Geomechanical and Geochemical Evidence of Piezonuclear Fission Reactions in the Earth's Crust

A. Carpinteri and A. Manuello

Politecnico di Torino, Department of Structural Engineering & Geotechnics, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

ABSTRACT: Piezonuclear reactions, which occur in inert and non-radioactive elements, are induced by high pressure and, in particular, by brittle fracture phenomena in solids under compression. These low-energy reactions generally take place in nuclei with an atomic weight that is lower or equal to that of iron (Fe). The experimental evidence, obtained from repeatable measurements of neutron emissions [*Strain* 45, 2009, 332; *Strain* (in press); Phys. Lett. A. 373, 2009, 4158], can be also recognised considering the anomalous chemical balances of the major events that have affected the Earth's crust, oceans and atmosphere, over the last 4 billion years. These anomalies include (i) abrupt variations in the most abundant elements in correspondence with the formation of tectonic plates; (ii) the 'Great Oxidation Event' (2.7–2.4 billion years ago), with a sharp increase in atmospheric oxygen and the subsequent origin of life; (iii) the current climate acceleration partially because of 'carbon pollution'. Natural piezonuclear reactions are induced by fault sliding and plate subduction phenomena.

KEY WORDS: *carbon pollution, element evolution, Great Oxidation Event, neutron emissions, piezonuclear reactions, plate tectonics, rocks crushing*

Introduction

Over the last century, most recent scientific disciplines such as cosmology, astrophysics, and geology, have tried to answer questions concerning the origin of the Earth and the universe [1, 2]. Such questions have now given place to interrogatives concerning the substance that composes the universe, the heterogeneous distribution of the main elements on the Earth, and their evolution in time [1, 3–7].

The Earth's composition and its way of evolving throughout the geologic eras are topics that give rise to an abundancy of questions that have remained unanswered [3, 7]. In fact, we still do not know whether the distribution of the constituent elements is the result of the initial formation phases of the proto-Earth, or if it is the effect of slow transformations that started to occur after the beginning of terrestrial evolution, about 4.57 billion years (Gyrs) ago [5–7].

Significant events, such as the Great Oxidation Event (GOE), in which 10^5-fold increase in the concentration of oxygen took place in the Earth's atmosphere between 2.7 and 2.4 Gyrs ago [8–12], the strong iron depletion in the composition of the oceans and Earth's crust [6, 10, 13, 14], and the drastic decrease in nickel [14, 15], are just some of the major events pertaining to the Earth's dynamics and the evolution of chemical elements that have remained unresolved.

In this work, which is based on recent studies by Carpinteri *et al.* [16, 17] and Cardone *et al.* [18] concerning piezonuclear fission reactions, a geophysical and geological explanation is proposed to the main compositional variations in the Earth's crust and atmosphere, from their origin until present times.

It has been shown that pressure, exerted on radioactive or inert media, can generate nuclear reactions and reproducible neutron emissions. In particular, low-energy nuclear reactions and heat generation have been verified in pressurised deuterium gas by Arata *et al.* [19, 20] and in radioactive deuterium-containing liquids during ultrasounds and cavitation by Taleyarkhan *et al.* [21]. The experiments recently proposed by Carpinteri *et al.* [16] and by Cardone *et al.* [18] follow a different path from those of other research teams and represent the first evidence of piezonuclear reactions and neutron emissions in inert, stable, and non-radioactive solids under compression, as well as in non-radioactive liquids during ultrasound cavitation [22, 23].

Neutron emission measurements, by means of helium-3 neutron detectors, have recently been performed on solid test specimens during crushing failure [16, 18]. These relevant results in particular regard neutron emissions from granite (gneiss) specimens that should be caused by 'nucleolysis' or piezonuclear 'fissions', occurred in the tested material, transforming heavier (Fe) into lighter (Mg, Al, Si) atoms. These reactions – less infrequent than we could think – would be activated where the environment conditions (pressure and temperature) are particularly severe, and mechanical phenomena of fracture, crushing, fragmentation, comminution, erosion, friction, etc., may occur. [16–18].

From this point of view, piezonuclear reactions, induced by the sliding of faults and plate subduction phenomena at the Earth' crust scale, could imply the different mineral reservoir locations on the Earth's surface and the most significant chemical element evolutions over the past 4.57 Gyrs (Earth's lifetime). The geomechanical and geochemical evidence shown in this paper involves not only the most abundant elements in the Earth's crust such as Si, Al, Mg, Fe, Ca, K, and Na but also the most important components of the Earth's atmosphere (N, O, and C). Piezonuclear reactions, induced by tectonic activity, could explain the great variations that have taken place in the composition of the early Earth's atmosphere, and the current climate acceleration partially because of CO_2 emissions. In this way, plate tectonics and the connected plate collision and subduction phenomena are useful to understand not only the morphology of our planet but also its compositional evolution.

Piezonuclear Reactions: From the Laboratory to the Earth Scale

Neutron emission measurements from brittle fracture

In the recent papers by Carpinteri *et al.* and by Cardone *et al.* [16, 18], the neutron measurements obtained from two granite specimens under compressive loading condition have exceeded the neutron background by approximately one order of magnitude, in correspondence to their brittle failure [16, 18]. These early results on piezonuclear reactions from brittle fractures of green Luserna granite (gneiss) specimens may be accounted for by the catastrophic nature of the failure [24–26]. From this experimental evidence, it can clearly be seen that piezonuclear reactions that give rise to neutron emissions are possible in inert non-radioactive solids [16, 18], in addition to liquids [22, 23]. In this case, an important aspect that should be taken into account is the composition of the materials in which the piezonuclear reactions have occurred. Green Luserna granite contains a considerable amount of iron oxides (~3% of Fe_2O_3, as total Fe) [27]. The iron content of the green Luserna granite used in the piezonuclear experiments could contribute to the phenomenon in question, in analogy with the case of piezonuclear reactions in liquids [22, 23]. Piezonuclear reactions with neutron emissions have in fact been obtained in liquids containing iron chloride or iron nitrate and subjected to ultrasounds and cavitation [22, 23]. In these experiments on liquid solutions, aluminium atoms appeared at the end in a final quantity as large as about seven times the small initial quantity (Cardone, F., Mignani, R., Petrucci, A. private communication). Similarly, for the fracture experiments on green Luserna Granite specimens [16, 18], analysis of the fracture surfaces, conducted by energy dispersive X-ray spectroscopy, has shown a considerable reduction in the iron content (25%) [28]. This iron decrease is counterbalanced by an increase in aluminium, silicon, and magnesium. In particular, the increase in aluminium content corresponds to the 85% of the iron decrease. Therefore, the piezonuclear fission reactions:

$$\mathrm{Fe}_{26}^{56} \rightarrow 2\,\mathrm{Al}_{13}^{27} + 2\ \text{neutrons} \tag{1}$$

$$\mathrm{Fe}_{26}^{56} \rightarrow \mathrm{Mg}_{12}^{24} + \mathrm{Si}_{14}^{28} + 4\,\text{neutrons} \tag{2}$$

should have occurred [16, 18].

Considering that granite, which is predominantly constituted by quartz and feldspar minerals, is a common and widely occurring type of intrusive, Sialic, igneous rock and that it is characterised by an extensive concentration in the rocks that make up the Earth's crust (~60% of the Earth's crust), the piezonuclear fission reactions expressed previously can be generalised from the laboratory to the Earth's crust scale, where mechanical phenomena of brittle fracture, because of fault collision and subduction, take place continuously in most seismic areas [29–31].

This hypothesis seems to find surprising evidence and confirmation from both the geomechanical and the geochemical points of view.

The neutron emissions involved in piezonuclear reactions can be detected not only in laboratory experiments, as shown in [16–18], but also at the Earth's crust scale. Recent neutron emission detections by Kuzhevskij *et al.* [32, 33] have led to consider also the Earth's crust, in addition to cosmic rays, as being a relevant source of neutron flux variations. Neutron emissions measured near the Earth's surface exceeded the neutron background by about one order of magnitude in correspondence with seismic

 | **Strain** (2011) **47** (Suppl. 2), 267–281
doi: 10.1111/j.1475-1305.2010.00766.x

activity and more appreciable earthquakes [34]. This relationship between the processes in the Earth's crust and neutron flux variations has allowed increasing tectonic activity to be detected and methods for short-term prediction and monitoring of earthquakes to be developed [33, 34].

Chemical composition of the Earth's continental and oceanic crust

Neutron flux variations, in correspondence with seismic activity, may be evidence of changes in the chemical composition of the crust, as a result of piezonuclear reactions.

The mass percentage concentrations of the most common chemical elements and oxides in the Earth's oceanic and continental crust are reported in Figure 1A,B and in Tables 1 and 2. The present natural abundances of aluminium (~8%), silicon (28%), and magnesium (1.3%) and scarcity of iron (~4%) in the continental Earth's crust (Figure 1B) are possibly due to the piezonuclear fission reactions (1,2) expressed previously. In addition, considering the mass percentage concentrations of other chemical elements, such as Na (~2.9%), Ni (~0.01%), and Co (0.003%), in the continental crust [3–6, 29–31] (see Figure 1B, Tables 1 and 2), it is possible to conjecture additional piezonuclear fission reactions that could take place in correspondence with plate collision and subduction:

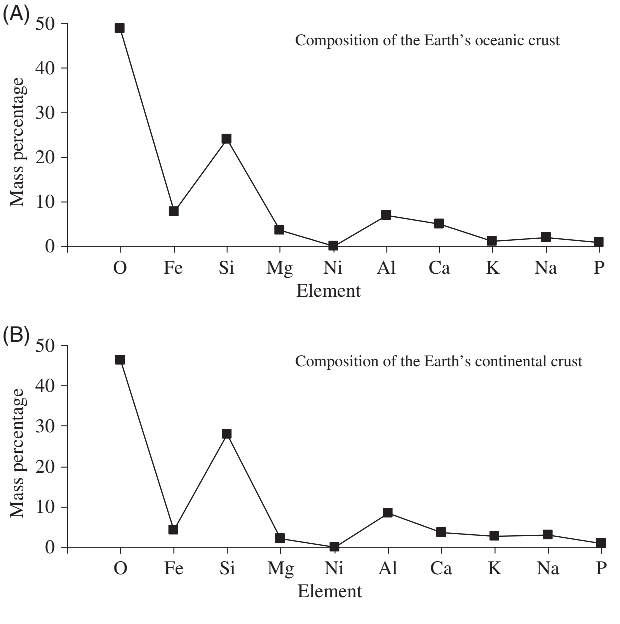

Figure 1: Mass percentage concentrations of the most common elements in the Earth's oceanic (A) and continental (B) crust [3, 5, 31]

$$\mathrm{Co}_{27}^{59} \rightarrow \mathrm{Al}_{13}^{27} + \mathrm{Si}_{14}^{28} + 4\,\text{neutrons} \tag{3}$$

$$\mathrm{Ni}_{28}^{59} \rightarrow 2\,\mathrm{Si}_{14}^{28} + 3\,\text{neutrons} \tag{4}$$

$$\mathrm{Ni}_{28}^{59} \rightarrow \mathrm{Na}_{11}^{23} + \mathrm{Cl}_{17}^{35} + 1\,\text{neutron} \tag{5}$$

The large concentrations of granite minerals, such as quartz and feldspar (SiO_2, Al_2O_3) in the Earth's crust and to a lesser extent of magnesite, halite, and zeolite (MgO, Na_2O, Cl_2O_3), and the low concentrations of magnetite, haematite, bunsenite, and cobaltite minerals (composed predominantly of Fe, Co, and Ni molecules) could be ascribed to piezonuclear reactions (1–5) due to tectonic and subduction phenomena.

To recognise the effects of piezonuclear reactions on the Earth's crust, the differences in chemical

Table 1: Chemical composition of the Earth's oceanic and continental crust (oxides)

Oxide	Molecular mass	Oceanic crust mass concentration (%)	Continental crust mass concentration (%)
SiO_2	60	49.40	46.60
TiO_2	80	1.70	0.60
Al_2O_3	102	15.40	16.00
FeO	72	10.10	5.00
MnO	71	0.18	0.10
MgO	40	7.60	2.80
CaO	56	11.20	4.70
Na_2O	62	2.60	3.00
K_2O	94	0.30	1.90
P_2O_5	156	0.35	0.10

Table 2: Chemical composition of the Earth's oceanic and continental crust (elements)

Most abundant elements			
Element	*Z*	Oceanic crust mass concentration (%)	Continental crust mass concentration (%)
O	6	49.50	47.00
Fe	26	7.80	4.00
Si	14	24.00	28.00
Mg	12	3.60	1.30
Ni	28	0.03	0.01
Al	13	7.00	8.30
Ca	20	8.90	3.00
K	19	0.10	2.80
Na	11	1.00	2.90
P	15	0.90	0.80
Co	27	–	0.003

composition between the continental and oceanic crust have to be considered. The oceanic crust is mainly composed of basaltic sediments (with high percentages of FeO and MgO) with a density of about 3 g cm^{-3} (Figure 1A). The continental crust, instead, which has a density of $\sim$2.5 g cm^{-3}, presents a Sialic or granitic composition (very high concentrations of Al and Si oxides), see Figure 1B [3, 29]. These two kinds of Earth's crust differ not only because of the dating of the sediments but also because of the geological processes by which they were formed [3–5, 31, 35–38].

At the sea bottom, the 85% of the Earth's volcanic eruptions take place in correspondence with mid-ocean ridges [35]. These submarine volcanoes generate the solid underpinnings of all the Earth's oceans, massive slabs of rocks that are generally <10 km thick (oceanic crust). The sediments that constitute the oceanic crust come into collision (subduction) with the continental plates that are sinking into the Earth's mantle. Very high pressures are developed during this phenomenon, because of the continuous impacts (seismic activity) between the oceanic plates and the continental littorals [3, 30, 38–40]. Part of the oceanic crust is actually melted inside the upper mantle, while the remaining 'accretionary wedge' provokes continental growth (accretionary model) [3–5, 32–35]. Comparing the data shown in Figure 1A,B concerning the composition of the two different types of terrestrial crust, it can be noted that the iron concentration changes from $\sim$4%, in the continental crust, to $\sim$8%, in the oceanic one, with a relative increase of 100%. Ni changes from $\sim$0.01%, in the continental crust (see Table 2), to $\sim$0.03%, in the oceanic one (about a threefold increase). Conversely, Al, Si, and Na vary from $\sim$7, $\sim$24, and $\sim$1% in the oceanic crust to $\sim$8, $\sim$28, and $\sim$2.9% in the continental crust, respectively.

Considering that approximatively 50% of the continental crust has originated over the last 3.8 Gyrs, as a result of oceanic crust subduction [3–5, 38–40], the considerable variations in the composition of the oceanic to the continental crust would seem to remain a mystery [35].

The authors' opinion is that piezonuclear reactions (1–5) could explain this particular phenomenon. Thus, the higher concentrations of Si, Al, Na, and Cl oxides in the continental crust and the low percentages of Fe, Co, and Ni oxides could be considered as the piezonuclear effects of tectonic activity and subduction phenomena.

As far as the concentration of Mg, reported in Figure 1A,B and Tables 1 and 2, is concerned, its present abundances in the continental ($\sim$1.3%) and oceanic ($\sim$3.6%) crust seem to be in contrast to piezonuclear reaction (2). The reason for this is that the Mg balance is more complex than those of the other elements (Ni, Fe, Si, Al, Na, Cl). As will be seen in the following, Mg is involved in other piezonuclear reactions that could explain the global decrease in Mg concentration from the oceanic to the continental crust, over different geological eras. This fact provides important explanations concerning the composition of atmosphere in the past and the present natural CO_2 emissions.

Heterogeneity in the composition of the Earth's crust: Fe and Al reservoir locations

After having considered piezonuclear fission reactions, during plate tectonics, as a possible explanation for the anomalous compositional transition between the oceanic and continental crust, it appears also possible to explain the heterogeneity in the distribution of aluminium and iron minerals over the Earth's surface.

The location of Al and Fe mineral reservoirs seems to be closely connected to the geological periods when different continental zones were formed [38–44]. This fact would seem to suggest that our planet has undergone a continuous evolution from the most ancient geological regions, which currently reflect the continental cores that are rich in Fe reservoirs, to more recent or contemporary areas of the Earth's crust where the concentrations of Si and Al oxides present very high mass percentages [3]. The main iron reservoir locations (magnetite and haematite mines) are reported in Figure 2A. The most abundant iron reservoirs are located in north-central USA, eastern Canada, north-central Brazil, central Australia, Ukraine, Russia, Mongolia, and north-central China [41–44].

The main concentrations of Al oxides and rocky andesitic formations (the Rocky Mountains and the Andes, with a strong concentration of Al_2O_3 minerals), are shown in Figure 2B together with the most important subduction lines, plate tectonic trenches, and rifts [3, 38]. The largest bauxite and alumina mines are located in Jamaica, Mexico, the north-eastern littorals of Brazil, Guyana, the Gulf of Guinea, India, the Chinese littorals along the East China Sea, Greece, the south of Italy, the Philippines, New Guinea, and the Australian coast [3, 43].

The iron and bauxite mine locations shown in Figure 2A,B, respectively, offer important geophysical evidence that piezonuclear reactions have continuously taken place during the geological formation of the Earth's crust. The geographical

Strain (2011) **47** (Suppl. 2), 267–281
doi: 10.1111/j.1475-1305.2010.00766.x

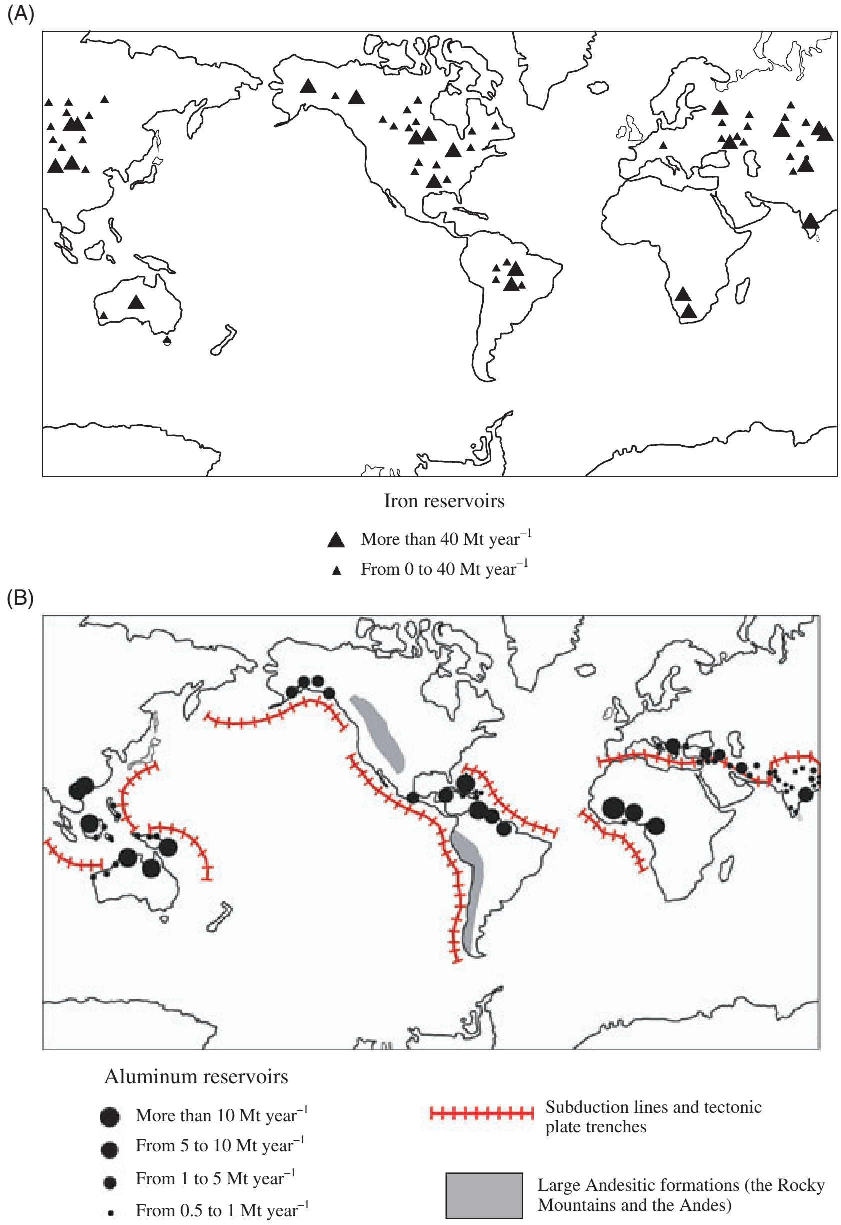

Figure 2: (A) Locations of the largest iron mines in the world [41–44]. Iron ore reservoirs (magnetite and haematite mines) are located in geographical areas with reduced seismic risks and always far from fault lines. (B) The largest aluminium (bauxite) reservoirs are reported together with the main Andesitic formations and most important subduction lines and plate tectonic trenches [3, 38, 43]. The largest Al reservoirs are located in correspondence with the most seismic areas and the largest faults

locations of main bauxite mines show that the largest concentrations of Al reservoirs can be found in correspondence with the most seismic areas of the Earth (Figure 2B). The main iron mines are instead exclusively located in the oldest and interior parts of continents (formed through the eruptive activity of the proto-Earth), in geographical areas with a reduced seismic risk and always far from the main fault lines. From this point of view, the close correlation between bauxite and andesitic reservoirs and the subduction and most seismic areas of the Earth's crust provides very impressive evidence of piezonuclear effects at the planetary scale.

Geochemical Evidence of Piezonuclear Reactions in the Evolution of the Earth's Crust

Planetary crusts in the solar system: the uniqueness of the Earth's continental crust

The chemical evolution of the Earth's crust is closely connected to the evolution of the solar system and it can be put in comparison with the composition of the crust of the other rocky planets and the Moon. According to recent studies [5], three types of crusts, conventionally divided into 'primary', 'secondary', and 'tertiary', may be distinguished within the solar system [5]. Primary crusts are characterised by a strong basaltic composition. Typical examples of primary planetary crusts are the ancient heavily cratered crust of Mars and some parts of the Lunar soils. These crusts are characterised by an iron mass concentration of about 15%. This value is much higher than the average iron concentration (~4%) that can be found in the Earth's crust. At the same time, this type of crust presents very low mass concentrations of Si and Al (~24 and ~4%, respectively). Recent studies on some of the Earth's ancient sediments would seem to suggest that the Earth's protocrust, in the Hadean period (4.5–3.8 Gyrs ago), had a chemical composition very similar to this primary type of crust [3–5, 45].

The Earth's oceanic crust and the present surface of Venus are typical examples of the secondary crust type. The tertiary crust is formed by subduction and melting of the secondary crust. The Earth's continental crust remains the only current example of tertiary crust in the solar system [3–5].

Many scientists agree that plate tectonics and continental subduction represent the main mechanisms responsible for the formation of the Earth's continental crust. Plate tectonics, which has been active on the Earth over the last 3.8 Gyrs, does not find any other correspondence in the other explored celestial bodies [3–5]. The crucial difference is that the Earth's crust seems to be the result of a constantly evolving process from a strong basaltic composition (early Earth) to a Sialic one (today). The surfaces of other celestial bodies (planets and satellites) are in a 'stagnant-lid regime' and represent a faithful model of the conditions in which the Earth was more than 3.8 Gyrs ago.

The evolution of the planetary crusts in the solar system is shown in Figure 3. The concentrations of Fe, Si, and Al in the proto-planets (from which the solar system planets descended), the Moon, Mars, and the Earth's crust are reported in the same figure. It can be seen that the concentration of Fe decreases as Si and Al concentrations increase moving towards the present Earth's crust composition (right side in Figure 3). On the contrary, Fe increases as Si and Al decrease, going back to the beginnings of our solar system, proto-planets and planet formations (left side in Figure 3).

Chemical evolution in the Earth's crust over the last 3.8 billion years

From 4.0 to 2.0 Gyrs ago, Fe could be considered one of the most common bio-essential elements required for the metabolic action of all living organisms [8, 11, 13, 46–48]. Today, the deficiency of this nutrient suggests it as a limiting factor for the development of marine phytoplankton and life on Earth [6, 10].

Elements such as Fe and Ni in the Earth's protocrust had higher concentrations in the Hadean (4.5–3.8 Gyr ago) and Archean (3.8–2.5 Gyr ago)

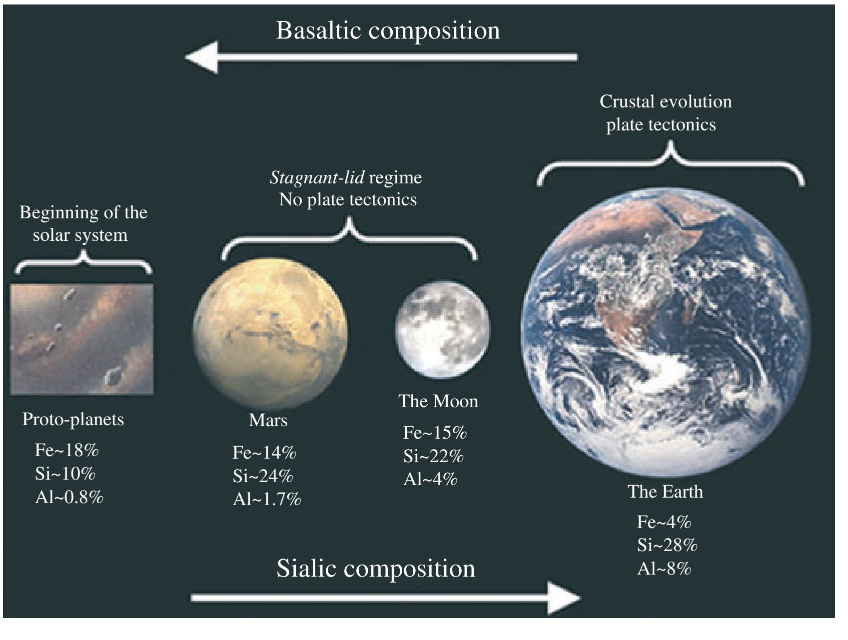

Figure 3: Iron concentrations in the proto-planets (from which the planets of the solar system have descended), the Moon, Mars, and the Earth's crust. Fe decreases while Si and Al concentrations increase moving towards the present Earth's crust composition (right side) [3–5]. Fe instead increases while Si and Al concentrations decrease, going back to the beginnings of our solar system, proto-planets and planet formations [4, 5] (left side)

| *Strain* (2011) **47** (Suppl. 2), 267–281
doi: 10.1111/j.1475-1305.2010.00766.x

periods compared to the present values [4, 5, 8, 11, 49–52]. The Si and Al concentrations instead were lower than they are today [3–5].

The estimated concentrations of Fe, Ni, Al, and Si in the Hadean and Archean Earth's protocrust and in the Earth's continental crust are reported in Figure 4. The data for the Hadean period (4.5–3.8 Gyrs ago) are referred to the composition of Earth's protocrust, considering the assumptions made by Foing and by Taylor and Mclennan [4, 45]. According to these authors, the Mars' and Moon's crusts are considered to be representative of the composition of the early Earth's protocrust (Hadean Eon) [4, 45].

In the same Figure, for the Archean period (3.8–2.5 Gyrs ago), the data are referred to compositional analysis of Archean sediments [3–5, 14, 15, 31, 53, 54]. For the last period from 2.5 Gyrs ago to today, the mass percentage concentrations of Fe, Ni, Al, and Si are referred to the present composition of Earth's continental crust [3–5, 29, 54].

A clear transition from a more basaltic condition (high concentrations of Fe and Ni) to a Sialic one (high concentrations of Al and Si) can be observed during the lifetime of our planet [3–5, 14, 15, 30, 31, 46–55].

The most abrupt changes in element concentrations shown in Figure 4 appear to be intimately connected to the tectonic activity of the Earth. The vertical drops in the concentrations of Fe and Ni, as well as the vertical jumps in the concentrations of Si and Al, 3.8 Gyrs ago, coincide with the time that many scientists have pointed out as the beginning of tectonic activity on the Earth. The subsequent abrupt transitions 2.5 Gyrs ago coincide with the period of the Earth's largest tectonic activity [4, 5].

As shown in Figure 4, the decrease in the mass concentration of iron and nickel is balanced by Al and Si increases and assuming an increase in Mg, according to reaction (2), equal to that of Si over the Earth s lifetime. A total decrease of ∼7% in Fe and Ni

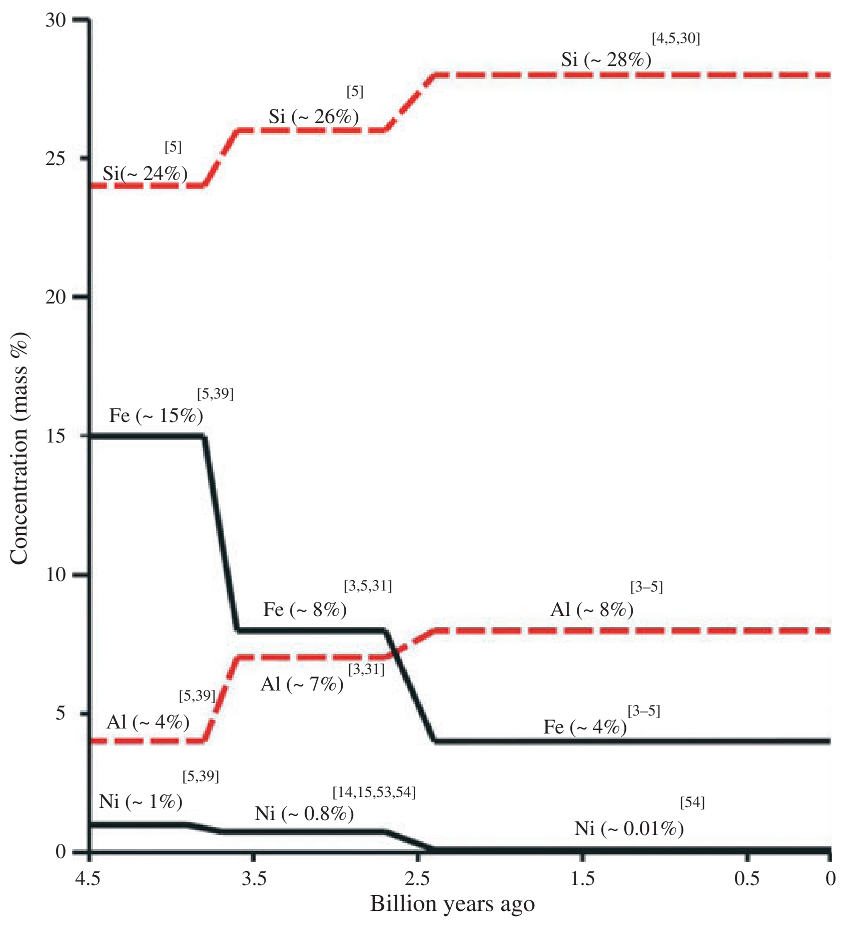

Figure 4: The estimated concentrations of Fe, Ni, Al, and Si in the Hadean and Archean Earth's protocrust and in the Earth's continental crust are reported. The Archean Earth's protocrust (3.8–4.5 Gyrs ago) had a less basaltic composition (Fe ∼8%, Ni ∼0.8%, Al ∼7%, Si ∼26%) [3, 5, 14, 15, 31, 53, 54] compared to the previous period (Hadean Era, 4.5–3.8 Gyrs ago) [5, 39] and a less Sialic composition compared to the concentrations in the Earth's continental crust today: Fe ∼4%, Ni ∼0.01%, Al ∼8%, Si ∼28%. [3–5, 30, 54]. Considering piezonuclear reactions (1,2,4), the overall 12% decrease in the heavier elements (Fe and Ni) is balanced by the Al and Si increases and assuming an increase in Mg, according to reaction (2), equal to that of Si over the last 4.5 Billion years

doi: 10.1111/j.1475-1305.2010.00766.x

concentrations and a relative increase of ~7% in the lighter chemical element concentrations (Si, Mg and Al) can be considered by piezonuclear reactions (1), (2), (4) and by the data shown in Figure 4 between the Hadean period (Hadean Eon, 4.5–3.8 Gyrs ago) and the Archean period (Archean Eon, 3.8–2.5 Gyrs ago). Similarly, a decrease of ~5% in the heavier elements (Fe and Ni) and a related increase (~5%) in the concentrations of lighter ones (Si, Mg and Al) can be considered between the Archean period (Archean Eon, 3.8–2.5 billion years ago) and more recent times (Figure 4). The Earth's protocrust in the Hadean era was strongly basaltic, similar to the composition of proto-planets (chondrites) [4, 45].

In particular, piezonuclear reactions (1,2,4) seem to be the cause of the abrupt variations shown in Figure 4. Piezonuclear reaction (2) implies that not only should the Si mass percentage increase overall by about 3.5% but also that of Mg. However, the latter increase, due to piezonuclear reaction (2), cannot be revealed from geological data of sediments in the Earth's continental crust. The most probable explanation is that Mg is not only a resulting element, as shown by piezonuclear reaction (2), but can also be considered as a starting element of another possible piezonuclear reaction:

$$Mg_{12}^{24} \rightarrow 2C_6^{12} \tag{6}$$

Reaction (6) could be very important for the evolution of both the Earth's crust and the atmosphere and considered as a valid explanation for the high level of CO_2 concentration (~15%) in the Archean Earth's atmosphere [56]. In addition, the large amount of C produced by Mg transformation (~3.5% of the Earth's crust) has undergone a slow but continuous diminishing in the CO_2 composition of the Earth's atmosphere, as a result of the escape that also involves other atmospheric gases like He and H [57].

Piezonuclear reaction (6) can also be put into correlation with the increase in seismic activity that has occurred over the last century [58]. Very recent evidence has shown CO_2 emissions in correspondence with seismic activity [59]: significant changes in the diffuse emission of carbon dioxide were recorded in a geochemical station at El Hierro, in the Canary Islands, before the occurrence of several seismic events during the year 2004. Appreciable precursory CO_2 emissions were observed to start before seismic events of relevant magnitude and to reach their maximum values some days before the earthquakes [59].

Relation (6) is not the only piezonuclear reaction that involves Mg as a starting element. Like the considerations made for the concentrations of elements such as Fe, Ni, Al, and Si (Figure 4), it is also possible to consider other elements such as Mg, Ca, Na, K, and O, which are involved in other piezonuclear reactions that have been assumed to occur in the chemical evolution of the Earth's crust.

The variations in mass percentage concentration for Mg, Ca, Na, K, and O in the Hadean and Archean Earth's protocrust and in the Earth's continental crust are reported in Figure 5, analogously to Figure 4 [3–5, 55]. The decrease in the mass concentrations of Mg and Ca has been balanced by an increase in Na, K, and O, during the Earth's lifetime. In particular, between the Hadean (4.5–3.8 Gyr ago) and the Archean era (3.8–2.5 Gyrs ago), and between the latter and more recent times, it is possible to observe an overall decrease of ~4.7% for Mg and ~4% for Ca. This decrease in the two alkaline-earth metals (Mg and Ca) seems to be nearly perfectly balanced by the increase in the concentrations of the two alkaline metals, Na and K (which have increased by 2.7 and 2.8%, respectively), and by a total increase (~3%) in

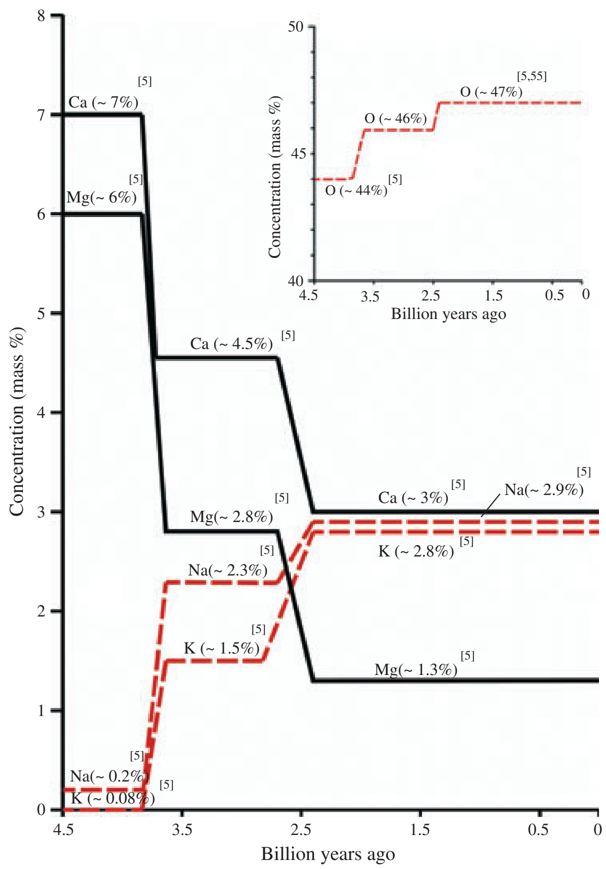

Figure 5: The variations in mass percentage concentration for Mg, Ca, Na, K, and O in the Hadean and Archean Earth's protocrust and in the Earth's continental crust are reported. It can be noted in particular that, considering piezonuclear reactions (7–10), the overall 8.7% decrease in alkaline-earth metals (Mg and Ca) is balanced by the Na, K, and O increase (~8.5%) [3–5, 55]

 Strain (2011) **47** (Suppl. 2), 267–281
doi: 10.1111/j.1475-1305.2010.00766.x

O, which has varied from ~44 to ~47% (the latter being the present oxygen concentration in the Earth's crust) (Figure 5).

From a close examination of the data reported in Figure 5, it is possible to conjecture a series of piezonuclear fission reactions that could represent the real origin of the sharp fluctuations of these chemical elements in the evolution of the Earth's crust:

$$\mathrm{Mg}_{12}^{24} \rightarrow \mathrm{Na}_{11}^{23} + \mathrm{H}_1^1 \quad (7)$$

$$\mathrm{Mg}_{12}^{24} \rightarrow \mathrm{O}_8^{16} + 4\mathrm{H}_1^1 + 4 \text{ neutrons} \quad (8)$$

$$\mathrm{Ca}_{20}^{40} \rightarrow \mathrm{K}_{19}^{39} + \mathrm{H}_1^1 \quad (9)$$

$$\mathrm{Ca}_{20}^{40} \rightarrow 2\mathrm{O}_8^{16} + 4\mathrm{H}_1^1 + 4 \text{ neutrons} \quad (10)$$

In particular, it can be noted that, considering piezonuclear reactions (7–10), an overall decrease in alkaline-earth metals (Mg and Ca) of about 8.7% is balanced by an increase in Na, K, and O of ~8.5% (see Figure 5). Taking into account a density of 3600 kg m^{-3} and a thickness of 60 km for the Hadean and Archean crusts, it is possible to estimate the mass of the early Earth's proto-crust as $\sim 1.08 \times 10^{23}$ kg. Considering this value, the decrease in Ca concentration, 1.3% of the Hadean and Archean proto-crust ($\sim 1.41 \times 10^{21}$ kg), corresponds very closely to the mass of water in oceans ($\sim 1.35 \times 10^{21}$ kg). In this way, reaction (10) could be considered responsible for the formation of oceans during the Earth's life time.

In addition, other piezonuclear reactions involving Si and Al as starting elements and C, N, O, H, and He as resultants can be considered:

$$\mathrm{Si}_{14}^{28} \rightarrow 2\ \mathrm{N}_7^{14} \quad (11)$$

$$\mathrm{Si}_{14}^{28} \rightarrow \mathrm{C}_6^{12} + \mathrm{O}_8^{16} \quad (12)$$

$$\mathrm{Si}_{14}^{28} \rightarrow \mathrm{O}_8^{16} + 2\mathrm{He}_2^4 + 2\mathrm{H}_1^1 + 2 \text{ neutrons} \quad (13)$$

$$\mathrm{Al}_{13}^{27} \rightarrow \mathrm{C}_6^{12} + \mathrm{N}_7^{14} + 1 \text{ neutron} \quad (14)$$

Piezonuclear reactions (1–10) are those that have affected the evolution of the Earth's crust over the last 4.5 billion years to the greatest extent. In particular, considering the data shown in Figures 4 and 5, it can be noted that reactions (1, 2, 4, 7–10) have been particularly recurrent and responsible for a variation of about 20% in the chemical composition of the Earth's crust. Piezonuclear reactions (11–14) have instead played a negligible role in the compositional variations of the Earth's crust but are of great importance as far as the increase in H, He, C, N, and O concentrations is concerned and for the evolution of the Earth's atmosphere.

The piezonuclear fission reactions identified by the authors can be subdivided into two sets, considering the starting and resulting elements. In the first jump, the starting elements are Fe, Co, and Ni, whereas the resulting elements are Mg, Al, and Si, as shown in reactions (1–5).

The reactions belonging to the second piezonuclear jump involve Mg, Al, Si and Ca as the starting elements, as well as C, N, O, H, and He as the resulting elements (reactions 6–14).

In short, two piezonuclear fission reaction jumps that are typical of the Earth's crust can be recognised:

$$\mathrm{Fe}_{26},\ \mathrm{Co}_{27}, \mathrm{Ni}_{28} \rightarrow \mathrm{Mg}_{12}, \mathrm{Al}_{13}, \mathrm{Si}_{14} \rightarrow \mathrm{C}_6, \mathrm{N}_7, \mathrm{O}_8$$

These two piezonuclear jumps represent not only the compositional variations of the Earth's crust over the last four billion years but also reflect the chemical composition of the Earth from its internal nucleus to its external surface, and atmosphere: nucleus (Ni-Fe and Co alloys), mantle (Si-Ma), crust (Si-Al), and atmosphere (C, N, O).

Considering the estimated temperature evolution of the Earth's surface and the Earth's continental crust growth reported in Figure 6 [5, 40, 60], together with the previously assumed piezonuclear jumps, it is possible to conjecture how tectonic plates formed in a first phase of minor seismic activity of the Earth (from 4.5 to 3.0 Gyrs ago) and during the second phase of diffused seismic and subduction activity (from 3.0 Gyrs ago to the present time). The starting elements involved in the first piezonuclear jump are Fe, Co, and Ni. It can be observed that these three elements, together with Si, solidify at temperatures higher than those of other elements such as Ca, Al, and Mg. The initial condition that existed in the primordial state of the Earth was that of a vast magma ocean which covered the Earth's surface. After a relatively short time, compared to the Earth's entire age, Fe, Co, Ni, and Si solidified from the primordial magma ocean and formed initial, small, tectonic plates. The first sporadic tectonic activity gave rise to the first

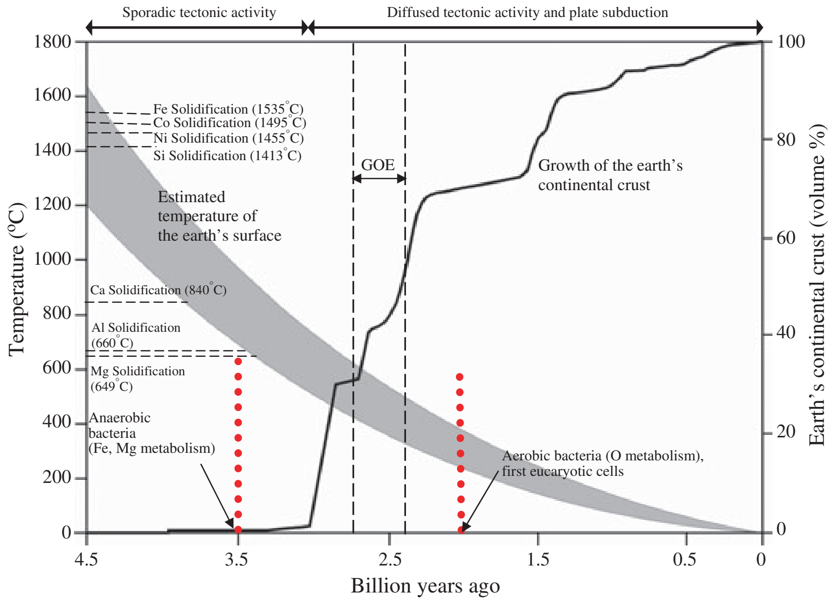

Figure 6: The estimated temperature of the Earth's surface and the growth of the Earth's continental crust volume are reported [5, 40, 60]. The solidification temperatures of Fe, Co, Ni, Si, Ca, Al, and Mg are also shown in the same plot

piezonuclear reactions (1–5, 11–13). Only later, between 3.5 and 3.0 Gyrs ago, did the solidifications of Ca, Al, and Mg took place in the Earth's proto-crust. Plate tectonics and subduction phenomena became diffused in correspondence with this fact and contributed to the fast accretion of the Earth's continental crust (between 3.0 and 2.5 Gyrs ago). At the same time, piezonuclear reactions (6, 8, 10–14) can explain the Great Oxidation Event that occurred between 2.7 and 2.4 Gyrs ago, the high level of CO_2 in the Archean Earth's atmosphere, and the present composition of the Earth's atmosphere.

Piezonuclear Effects on the Chemical Evolution of the Earth's Atmosphere

Composition of the Earth's early atmosphere

Recent studies have revealed that not only the Earth's crust but also the Earth's atmosphere [9–11] and the concentrations of the basic elements for the development of life in the oceans [8–11] have drastically changed over the Earth's lifetime [1–5]. The origin and early evolution of oceans and atmospheres of terrestrial planets are classic unsolved problems in planetary sciences [56, 61, 62]. H_2O and CO_2 were the two most abundant volatile species on the early surfaces of Earth, Venus, and Mars, e.g., [55, 61–63], while C, O, and H are the most important elements for life on Earth today. A CO_2- and H_2O-rich atmosphere of the early Earth (Archean period) has been envisaged and supported by recent studies [56, 64]. Piezonuclear reactions (6–14) may be considered to explain the strong variations between the past and present composition of the Earth's atmosphere. After the formation of oceans, the early atmosphere of the Earth was predominantly formed by carbon compounds (CO_2 and CH_4). The amount of carbon (~3.5%), coming form piezonuclear reaction (6), spread into the early atmosphere implying an atmospheric pressure about 650 times greater than the present value [56].

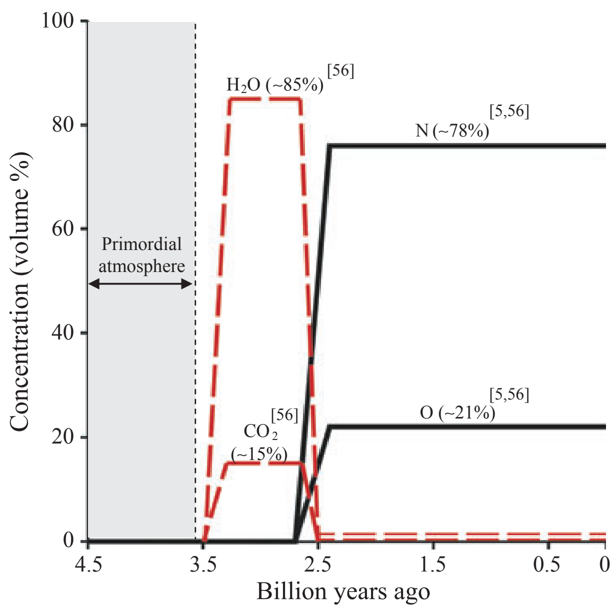

Figure 7: Variations in the atmospheric composition over the Earth's lifetime. During the Archean era, about 15% of the Earth's atmosphere was constituted by CO_2, and the remaining part was mainly composed of H_2O. The Earth's present atmospherical composition is dominated by nitrogen (N ~78%) and oxygen (O ~21%) [5, 56, 61, 62]

  Strain (2011) 47 (Suppl. 2), 267–281
doi: 10.1111/j.1475-1305.2010.00766.x

The variations in the atmospheric composition over the Earth's lifetime are reported in Figure 7. After the early Earth conditions, in which the primordial rarefied atmosphere was composed of H and He gases, it can be assumed that about 15% of the Earth's atmosphere was constituted by CO_2 during the Archean period, whereas the remaining part was mainly composed of H_2O and other minor components (see Figure 7). Considering the Earth's present atmospheric composition, which is dominated by nitrogen (N ~78%) and oxygen (O ~21%), it is possible to conclude that great variations have affected the Earth's atmosphere over the last 4.5 Gyrs.

Piezonuclear effects on greenhouse gases and the Earth's atmospheric evolution

Recent data have shown that CO_2 and H_2O concentrations increased dramatically between ~3.8 and ~2.5 Gyrs ago (Figure 7) in correspondence with sporadic seismic activity and the subduction of the primordial plates (Figure 6). Successively, between ~2.5 and ~2.0 Gyrs ago, the rapid increase in N and O concentrations may be considered to be closely related to the largest formation of the Earth's continental crust (Figures 6 and 7). The oxygen level, in fact, was very low during the Hadean and Archean eras (4.5–2.7 Gyr ago), but increased sharply (Great Oxidation Event) between 2.7 and 2.4 billion years ago, until the present concentration ~21% of the Earth's atmosphere was reached, a 10^5-fold higher value than that of the oxygen concentration in the earlier atmosphere (Figures 6 and 7).

During the same period (from 2.7 to 2.4 Gyrs ago), which represents 6% of the Earth's lifetime (4.57 Gyrs), 50% of the continental crustal volume formed in concomitance with the most intense tectonic and continental subduction activity (Figure 6). Considering this scenario approximately 2.0 Gyr ago, it is also possible to justify the origin of the first aerobic bacteria and multicellular eukaryotic organisms, ancestors of animals and human beings (Figure 6). Considering the composition variations in the Earth's atmosphere shown in Figure 7, and the piezonuclear fission reactions (6, 8, 10–14), it can be observed that the intense tectonic activity caused a sudden increase in CO_2 and later in the O and N levels in the Earth's atmosphere. While the O and N levels remained constant, the high CO_2 concentration, principally due to piezonuclear reaction (6), started to decrease after 2.5 Gyr ago (Figure 7). This fact can be explained considering the planetary air leak of gaseous elements and molecules, such as H,

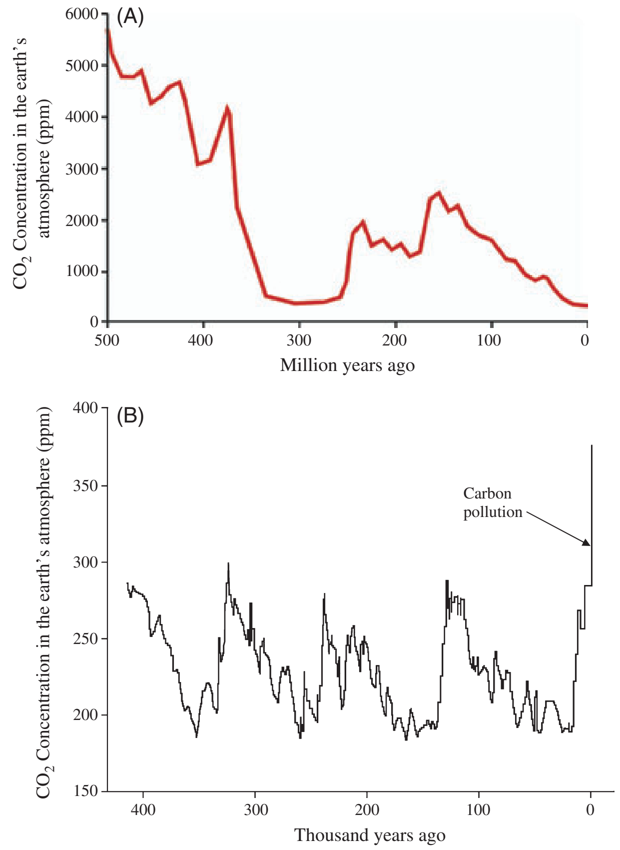

Figure 8: (A) CO_2 concentration in the Earth's atmosphere over the last 500 million years. The trend shown in the plot has been determined considering the database reported by Royer [65] together with the results of some geochemical models developed between 2001 and 2004 [66–70]. (B) CO_2 concentration in the Earth's atmosphere over the last 4×10^5 years [70, 71]

He, and CO_2, that has affected the atmosphere during the Earth's lifetime [57].

The continuous decrease in CO_2 concentration over the last 3.5 Gyrs has recently been contrasted by carbon pollution. The carbon dioxide (CO_2) variations over the last 500 million years (Phanerozoic period) are reported in Figure 8A. The trend shown in the plot has been determined considering Royer's database [65] together with the results of several geochemical models pertaining to CO_2 variations [66–68]. The present CO_2 concentration in the Earth's atmosphere is about 400 ppm, while 500 million years ago, it was about 6000 ppm. Observing the phenomenon at that time scale, the increase that has occurred over the last 100 years, and which has been ascribed to carbon emissions from the industrial revolution, seems to be negligible.

In Figure 8B, it is possible to observe the carbon dioxide (CO_2) variations over the last 4×10^5 years [69–71]. Today, some scientists sustain that, throughout the twentieth century, new forms of carbon pollution and the reactive nitrogen released into terrestrial environment by human activities (synthetic fertiliser, industrial use of ammonia) have been the only responsible for the dramatic increase in CO_2 and N in the contemporary Earth's atmosphere [61, 72]. However, a strong doubt remains that much of these CO_2 (about 3/4 of the total) and N (about 2/3 of the total) are provided by the same causes that have produced the previous cycles of carbon dioxide concentrations (Figure 8B) and the nitrogen increase in the Archean atmosphere (Figure 7) [56, 58].

Piezonuclear Effects on Nickel Depletion as Well as on Higher Salinity During Tectonic Plate Formation or in the Mediterranean Sea

Compositional and chemical analyses of ancient oceanic sediments have shown that the concentration level of salts, such as NaCl, in the Earth's oceans increased sharply from 1.5 to 2.0 times between ~2.7 and 2.4 Gyrs ago [73]. Direct evidence of this increase in the salinity level of Archean oceans can be found in the chemical data of fluid inclusions in quartz and crystals reported by Knauth [39, 73]. At the same time, the oceanic level of Ni compounds and nutrients strongly decreased by about 40-fold [14, 15].

Recent studies have also revealed how the Mediterranean Sea is the zone with the highest sea salinity concentration (NaCl) in the world [45]. Figure 9A shows the sea salinity level for the Mediterranean basin [74]. The salinity is expressed in p.s.u. (practical salinity unit), which represents the ratio of the sea water salinity to that of a standard solution. The salinity level in the Mediterranean Sea varies from a minimum of 36 to a maximum of 40 p.s.u. These are very high levels compared to the salinity of other sea waters on the Earth (average value ~35 p.s.u.) [45].

Figure 9B shows the seismic map of the main earthquakes that have occurred over the last fifteen years in the Mediterranean Fault area [75, 76]. The Mediterranean basin has been affected in particular by numerous and high-magnitude earthquakes because of collision between the Afro-Arabian plate, in the south, and the Eurasian plate, in the north. The Mediterranean fault contributes to make the Mediterranean basin one of the most dangerous areas in the World, from a seismic point of view. Considering piezonuclear reaction (5), it is possible to recognise that recent or ancient evidence of Ni depletion [14, 15] and the very high level of salinity in the Ionian and Aegean seas, close to areas subjected to large earthquakes (Southern Italy, Sicily, and Greece), may be correlated to piezonuclear reaction effects induced by the activity of Mediterranean Fault. Considering the NaCl concentration (3.8%) in the sea water, the mass of dissolved sodium chloride can be quantified in 5.14×10^{14} kg, this value corresponding to 0.05% of the Earth's proto-crust. In this way, a small part of the Ni decrease reported in Figure 4 can be accounted for the salinity level of oceans.

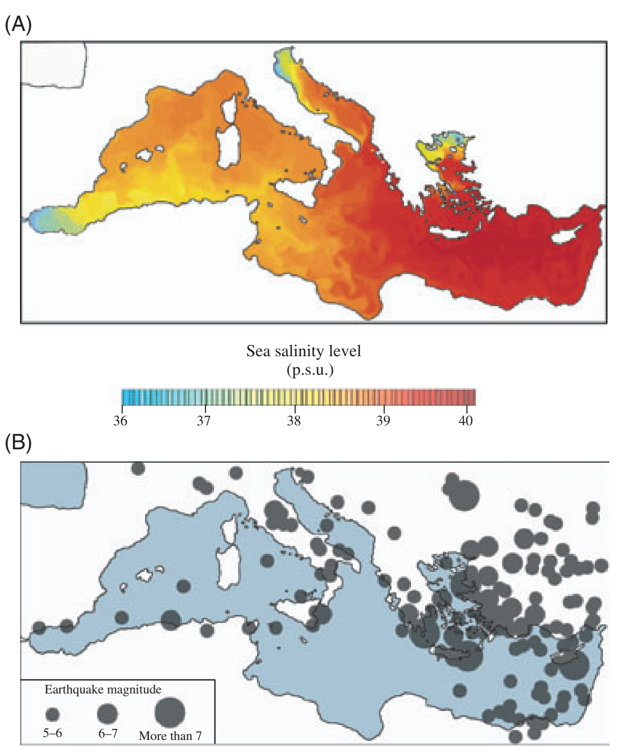

Figure 9: (A) Map of the salinity level in the Mediterranean Sea expressed in p.s.u. [74]. The Mediterranean basin is characterised by the highest sea salinity level in the world. (B) Seismic map of the major earthquakes that have occurred over the last fifteen years in the Mediterranean Fault area [75, 76]

Conclusions

The piezonuclear reactions, which have recently been discovered in the brittle failure of inert solids (gneiss) [16, 18], have been considered to interpret the most significant geophysical and geological evidence, today still unexplained. Two piezonuclear fission reaction jumps that are typical of the Earth's crust have been recognised. The first piezonuclear jump explains the large variations in the most abundant chemical elements (Fe, Si, Al) in the Earth's crust and the high salinity that has occurred during tectonic plate formation or, which can presently be found, in the Mediterranean basin. The second piezonuclear

doi: 10.1111/j.1475-1305.2010.00766.x

jump provides consistent explanations of the high nitrogen level in the Earth's present atmosphere, the Great Oxidation Event, and the high CO_2 level in the Archean atmosphere.

In addition, as shown by piezonuclear reactions (1,2), the fundamental starting element in the first piezonuclear jump was iron. This element plays also a crucial role in the stellar thermonuclear fusion process of small and medium-sized stars. Fe, in fact, is the heaviest element that is synthesised by thermonuclear fusion reactions before star collapse. This combustion product is the so-called *stellar ash* and is the material of which the proto-planets in the solar system were formed and from which they may have evolved, through piezonuclear reactions, to a Sialic condition (see the case of the Earth). Similarly, the atmospheric elements (C, N, O, H, and He) can be considered the '*planetary ashes*'. These gases are the results of the second piezonuclear jump, and they have gradually escaped from Earth into space through the planetary air leak [57].

Finally, through experimental and theoretical studies of neutron emission and piezonuclear fission reactions from brittle fracture, it will also be possible to explore new and fascinating application fields, such as: (i) short-term prediction and monitoring of earthquakes, (ii) realistic evaluation of the natural emission of black carbon and CO_2, with their effects on global pollution, (iii) production of neutrons for medical use in cancer therapy, (iv) disposal of radioactive wastes, (v) hypothetical production of clean nuclear energy.

Acknowledgements

The authors have not been financially supported by any specific grant or agency for the research work reported in this paper. However, they anticipatedly acknowledge any form of support for further future studies in the same directions.

REFERENCES

1. Kolb, E. (2000) *Blind Watchers of the Sky: The People and Ideas That Shaped Our View of the Universe*. Oxford University Press, Oxford.
2. Kolb, E., Matarrese, S., Notari, S. and Riotto, A. (2005) Primordial inflation explains why the Universe is accelerating today. arXiv:hep-th/0503117v1, 1–4.
3. Favero, G. and Jobstraibizer, P. (1996) The distribution of aluminum in the Earth: from cosmogenesis to Sial evolution. *Coord. Chem. Rev.* **149**, 367–400.
4. Taylor, S. R. and McLennan, S. M. (1995) The geochemical evolution of the continental crust. *Rev. Geophys.* **33**, 241–265.
5. Taylor, S. R. and McLennan, S. M. (2009) *Planetary Crusts: Their Composition, Origin and Evolution*. Cambridge University Press, Cambridge.
6. Anbar, A. D. (2008) Elements and evolution. *Science* **322**, 1481–1482.
7. Hawkesworth, C. J. and Kemp, A. I. S. (2006) Evolution of the continental crust. *Nature* **443**, 811–817.
8. Canfiled, D. E. (1998) A new model for Proterozoic ocean chemistry. *Nature* **396**, 450–453.
9. Williams, R. P. and Da Silva, F. J. R. (2003) Evolution was chemically constrained. *J. Theor. Biol.* **220**, 323–343.
10. Buesseler, K. O., Doney, S. C. and Karl, D. M. *et al.* (2008) Ocean iron fertilization moving forward in a sea of uncertainty. *Science* **319**, 162.
11. Holland, H. D. (2006) The oxygenation of the atmosphere and oceans. *Philos. Trans. R. Soc. Lond. Ser. B.* **361**, 903–915.
12. Kump, L. R. and Barley, M. E. (2007) Increased subaerial volcanism and the rise of atmospheric oxygen 2.5 billion years ago. *Nature* **448**, 1033–1036.
13. Kholodov, V. N. and Butuzova, G. Y. (2008) Siderite formation and evolution on sedimentary iron ore deposition in the Earth's history. *Geol. Ore Deposits* **50**, 299–319.
14. Konhauser, K. O., Pecoits, E., Lalonde, S. V., Papineau, D., Nisbet, E. G., Barley, M. E., Arndt, N. T., Zahnle, K. and Kamber, B. S. (2009) Oceanic nickel depletion and a methanogen famine before the Great Oxidation Event. *Nature* **458**, 750–754.
15. Saito, M. A. (2009) Less nickel for more oxygen. *Nature* **458**, 714–715.
16. Carpinteri, A., Cardone, F. and Lacidogna, G. (2009) Piezonuclear neutrons from brittle fracture: early results of mechanical compression tests. *Strain* **45**, 332–339, Presented also at the Turin Academy of Sciences on December 10, 2008, Proc. of the Turin Academy of Sciences, Ser. V, (2010) 33: 27–42.
17. Carpinteri, A., Lacidogna, G., Manuello, A. and Borla, O. (in press) Neutron emissions in rock specimens under monotonic, cyclic, and vibrational loading. *Strain*.
18. Cardone, F., Carpinteri, A. and Lacidogna, G. (2009) Piezonuclear neutrons from fracturing of inert solids. *Phys. Lett. A.* **373**, 4158–4163.
19. Arata, Y. and Zhang, Y. (1995) Achievement of solid-state plasma fusion ('cold-fusion'). *Proc. Jpn. Acad. Ser. B*, **71**, 304–309.
20. Arata, Y., Fujita, H. and Zhang, Y.-C. (2002) Intense deuterium nuclear fusion of pycnodeuterium-lumps coagulated locally within highly deuterated atom clusters. *Proc. Jpn. Acad. Ser. B*, **78**, 201–204.
21. Taleyarkhan, R. P., West, C. D., Cho, J. S., Lahey, R. T., Jr, Nigmatulin, R. I. and Block, R. C. (2002) Evidence for nuclear emissions during acoustic cavitation. *Science* **295**, 1868–1873.
22. Cardone, F., Cherubini, G. and Petrucci, A. (2009) Piezonuclear neutrons. *Phys. Lett. A.* **373**, 862–866, See also: F. Cardone *et al.* http://www.arxiv.org/abs/0710.5115.
23. Cardone, F. and Mignani, R. (2007) *Deformed Spacetime*. Springer, Dordrecht, Chapters 16–17.

24. Carpinteri, A. (1989) Cusp catastrophe interpretation of fracture instability. *J. Mech. Phys. Solids* **37**, 567–582.

25. Carpinteri, A. (1990) A catastrophe theory approach to fracture mechanics. *Int. J. Fract.* **44**, 57–69.

26. Carpinteri, A. and Corrado, M. (2009) An extended (fractal) overlapping crack model to describe crushing size-scale effects in compression. *Eng. Fail. Anal.* **16**, 2530–2540.

27. Vola, G. and Marchi, M. (2009) Mineralogical and petrographic quantitative analysis of a recycled aggregate from quarry wastes. The Luserna stone case-study. *Proc of the 12th Euroseminar on Microscopy Applied to Building Materials*, 15–19 September 2009, Dortmund, Germany.

28. Carpinteri, A., Chiodoni, A., Manuello, A. and Sandrone, R. Compositional and microchemical evidence of piezonuclear fission reactions in rock specimens subjected to compression tests. *Strain*. doi: 10.1111/j.1475-1305.2010.00767.x

29. Fowler, C. M. R. (2005) *The Solid Earth: An Introduction to Global Geophysics*. Cambridge University Press, Cambridge.

30. Doglioni, C., (2007) Interno della Terra, Treccani, Enciclopedia Scienza e Tecnica, 595–605.

31. Rudnick, R. L. and Fountain, D. M. (1995) Nature and composition of the continental crust: a lower crustal perspective. *Rev. Geophys.* **33**, 267–309.

32. Kuzhevskij, B. M., Nechaev, O. Yu., Sigaeva, E. A. and Zakharov, V. A. (2003) Neutron flux variations near the Earth's crust. A possible tectonic activity detection. *Nat. Hazards Earth Sys. Sci.* **3**, 637–645.

33. Kuzhevskij, B. M., Nechaev, O. Yu. and Sigaeva, E. A. (2003) Distribution of neutrons near the Earth's surface. *Nat. Hazards Earth Sys. Sci.* **3**, 255–262.

34. Volodichev, N. N., Kuzhevskij, B. M., Nechaev, O. Yu., Panasyuk, M. I., Podorolsky, A. N. and . Shavrin, P. I. (2000) Sun–Moon–Earth connections: the neutron intensity splashes and seismic activity. *Astron. Vestnik* **34**, 188–190.

35. Kelemen, P. B. (2009) The origin of the land under the sea. *Sci. Am.* **300**, 42–47.

36. Dupont, C. L., Yang, S., Plenik, B. and Bourne, P. E. (2006) Modern proteomes contain putative imprints of ancient shifts in trace metal geochemistry. *Proc. Natl Acad. Sci. USA* **103**, 17822–17827.

37. Broecker, W. S. (1985) *How to Build a Habitable Planet*. Eldigio Press, New York.

38. Lunine, E. J. I. (1998) *Earth: Evolution of a Habitable World*. Cambridge University Press, Cambridge, New York, Melbourne.

39. Hazen, R. M., Papineau, D., Bleeker, W., Downs, R. T., Ferry, J. M., McCoy, T. J., Sverjensky, D. A. and Yang, H. (2008) Mineral evolution. *Am. Mineral.* **93**, 1693–1720.

40. Condie, K. C. (1976) *Plate Tectonics and crustal evolution*. Pergamon Press, New York, Toronto, Oxford, Sydney, Braunshweig, Paris.

41. Roy, I., Sarkar, B. C. and Chattopadhyay, A. (2001) MINFO-a prototype mineral information database for iron ore resourcers of India. *Comput. Geosci.* **27**, 357–361.

42. World Iron Ore producers. Available at http://www.mapsofworld.com/minerals/world-iron-ore-producers.html; last accessed October 2009.

43. World Mineral Resources Map. Available at http://www.mapsofworld.com/world-mineral-map.htm; last accessed October 2009.

44. Key Iron Deposits of the World. Available at http://www.portergeo.com.au/tours/iron2002/-iron2002depm2b.asp; last accessed October 2009.

45. Foing, B. (2005) Earth's childhood attic. *Astrobiological Magazine*: Retrospection (on-line) February 23.

46. Sigman, D., Jaccard, S. and Haug, F. (2004) Polar ocean stratification in a cold climate. *Nature* **428**, 59–63.

47. Galimov, E. M. (2005) Redox evolution of the Earth caused by a multistage formation of its core. *Earth Planet. Sci. Lett.* **233**, 263–276.

48. Yamaguchi, K. E. (2005) Evolution of the geochemical cycle of Fe trough geological time: iron isotope perspective. *Front. Res. Earth Evol.* **2**, 4–24.

49. Basile-Doelsch, I. (2006) Si stable isotope in the Earth's surface: a review. *J. Geochem. Explor.* **88**, 252–256.

50. Basile-Doelsch, I., Meunier, J. D. and Parron, C. (2005) Another continental pool in the terrestrial silicon cycle. *Nature* **433**, 399–402.

51. De la Rocha, C. L., Brzezinski, M. and De Niro, M. J. (2000) A first look at the distribution of the stable isotopes of silicon in natural waters. *Geochim. Cosmochim. Acta* **64**, 2467–2477.

52. Ragueneau, O., Tréguer, P., Leyneart, A. *et al.* (2000) A review of the Si cycle in the modern ocean: recent progress and missing gaps in the application of biogenic opal as a paleoproductivity proxy. *Global Planet. Change* **26**, 317–365.

53. Egami, F. (1975) Minor elements and evolution. *J. Mol. Evol.* **4**, 113–120.

54. Natl Academy of Sciences (1975) . *Medical and Biological Effects of Environmental Pollutants: Nickel*. Proc. Natl Acad Sci., Washington, DC.

55. Yaroshevsky, A. A. (2006) Abundances of chemical elements in the Earth's crust. *Geochem. Int.* **44**, 54–62.

56. Liu, L. (2004) The inception of the oceans and CO_2-atmosphere in the early history of the Earth. *Earth Planet. Sci. Lett.* **227**, 179–184.

57. Catling, C. D. and Zahnle, K. J. (2009) The planetary air leak. *Sci. Am.* **300**, 24–31.

58. Aki, K. (1983) Strong motion seismology. In: *Earthquakes: Observation, Theory and Interpretation*. (H. Kanamori and E. Boschi, Ed.). North-Holland Pub. Co, Amsterdam: 223–250.

59. Padron, E., Melian, G., Marrero, R., Nolasco, D., Barrancos, J., Padilla, G., Hernandez, P. A. and Perez, N. M. (2008) Changes in the diffuse CO_2 emission and relation to seismic activity in and around El Hierro, Canary Islands. *Pure Appl. Geophys.* **165**, 95–114.

60. Grignè, C. and Labrosse, S. (2001) Effects of continents on Earth cooling: thermal blanketing and depletion in radioactive elements. *Geophys. Res. Lett.* **28**, 2707–2710.

61. Kasting, J. F. and Ackerman, T. P. (1986) Climatic consequences of very high carbon dioxide levels in the Earth's early atmosphere. *Science* **234**, 1383–1385.

62. Yung, Y. L. and De More, W. B. (1999) *Photochemistry of Planetary Atmospheres*. Oxford Univ. Press, New York.

doi: 10.1111/j.1475-1305.2010.00766.x

63. Holland, H. D. (1984) *The Chemical Evolution of the Atmosphere and Oceans*. Princeton Univ. Press, Princeton.
64. Abell, G. O. (1975) *Exploration of the Universe*. Holt, Rinehart & Winston, New York.
65. Royer, D. L., Berner, R. A., Montañez, I. P., Tabor, N. J. and Beerling, D. J. (2004) CO_2 as a primary driver of Phanerozoic climate. *GSA Today* **14**, 4–10.
66. Berner, R. A. (1990) Atmospheric carbon dioxide levels over Phanerozoic Time. *Science* **249**, 1382–1386.
67. Berner, R. A. and Kothavala, Z. (2001) GEOCARB III: a revised model of atmospheric CO_2 over Phanerozoic time. *Am. J. Sci.* **301**, 182–204.
68. Bergman, R. A., Noam, M., Timothy, M. L. and Watson, A. J. (2004) COPSE: a new model of biogeochemical cycling over Phanerozoic time. *Am. J. Sci.* **301**, 182–204.
69. Rothman, D. H. (2001) Atmospheric carbon dioxide levels for the last 500 million years. *Proc. Natl Acad. Sci. U.S.A.* **99**, 4167–4171.
70. Fischer, H., Wahlen, M., Smith, J., Mastroianni, D. and Deck, B. (1999) Ice core records of atmospheric CO_2 around the last three glacial terminations. *Science* **283**, 1712–1714.
71. Monnin, E., Steig, E. J., Siegenthaler, U. *et al.* (2004) Evidence for substantial accumulation rate variability in Antarctica during the Holocene, through synchronization of CO_2 in the Taylor Dome, Dome C and DML ice cores. *Earth Planet. Sci. Lett.* **224**, 45–54.
72. Townsend, A. and Howarth, R. W. (2010) Fixing the global Nitrogen problem. *Sci. Am.* **302**, 50–57.
73. Knauth, P. (1998) Salinity history of the Earth's early ocean. *Nature* **395**, 554–555.
74. Tel-Aviv University Weather Research Center (TAU WeRC). Available at http://wind.tau.ac.il/salt-ina/salt.html; last accessed October 2009.
75. European-Mediterranean Seismological Centre. Available at http://www.portergeo.com.au-/tours/iron2002/-iron2002depm2b.asp; last accessed October 2009.
76. Earthquake Hazards Program, Earthquake List & Maps. Available at http://earthquake.usgs.-gov/earthquakes/eqarchives/year; last accessed October 2009.