Correlation between the Fluctuations in Worldwide Seismicity and in Atmospheric Carbon Pollution

Sci

MDPI

Article

Correlation between the Fluctuations in Worldwide Seismicity and in Atmospheric Carbon Pollution

Alberto Carpinteri and Gianni Niccolini *

Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Turin, Italy; alberto.carpinteri@polito.it

* Correspondence: gianni.niccolini@polito.it; Tel.: +39-11-090-4910

Review Status: peer reviewing/peer reviewed

Reviewer 1 name: Accept/Accept after Revision/Reject

Reviewer 2 name: Accept/Accept after Revision/Reject

Reviewer 3 name: Accept/Accept after Revision/Reject

Received: date; Published: date (Version 1, doi: xx), date (Version 2, doi: xx), date (Version 3, doi: xx), ….

Abstract: Crucial stages in the geochemical evolution of the Earth's Crust, Ocean and Atmosphere could be explained in the light of assumed low-energy nuclear reactions (LENR) triggered by seismic activity. LENR result in the fission of medium weight elements accompanied by neutron emissions, involving Fe and Ni as starting elements, and C, N, O as resultants. Geochemical data and experimental evidences support the LENR hypothesis. The present time series analysis highlights significant correlation between the atmospheric CO_2 growth rate and the global seismic-moment release, whereas the trending behavior responds to the anthropogenic emissions. The fluctuations in the atmospheric CO_2 growth rate time series, inexplicable in terms of anthropogenic emissions, could be explained by cycles of worldwide seismicity, which massively triggers LENR in the Earth's Crust. In this framework, LENR from active faults must be considered as a relevant cause of carbon formation and degassing of freshly formed CO_2 during seismic activity.

Keywords: atmospheric evolution; seismicity; low-energy nuclear reactions; Carbon pollution; time series analysis

1. Introduction

Recent geochemistry studies have demonstrated that the Earth's crust and atmosphere have undergone significant changes in their chemical composition over the last 4.5 billion years [1–10]. Undoubtedly, one of the basic characteristics of the early stages of the Earth's formation was the presence of a highly toxic primordial atmosphere very different from today's, whose origin is still being investigated. Various hypotheses have been formulated regarding the variation in the atmospheric composition over the Earth's life time, such as degassing from volcanism [11,15], heavy bombardment by asteroids [16,17], and production of free oxygen by cyanobacterial photosynthesis leading to the Great Oxidation Event [18–20], none of them fully convincing and conclusive.

On the other hand, the changes in element concentrations appear to be intimately correlated to the tectonic activity of the Earth. Recent data on the composition time variations in the Earth's atmosphere have shown that CO_2 and H_2O concentrations in the atmosphere increased dramatically between 3.8 and 2.5 Gyr ago, between the tectonic plate formation and the most severe tectonic activity. This primordial Carbon pollution is related to drops in the concentrations of Fe and Ni as well as to jumps in the concentrations of Si and Al occurred in two step-wise transitions: 3.8 Gyr ago,

Commento [M1]: Please carefully check the accuracy of names and affiliations. Changes will not be possible after proofreading.

Commento [M2]: Newly added, and please add the post code before this city

Commento [M3]: Incorrect order, the references cited should be in order, please confirm and modify

at the beginning of tectonic activity, and then 2.5 Gyr ago, during the period of the most severe tectonic activity [21–26], as shown in Figure 1.

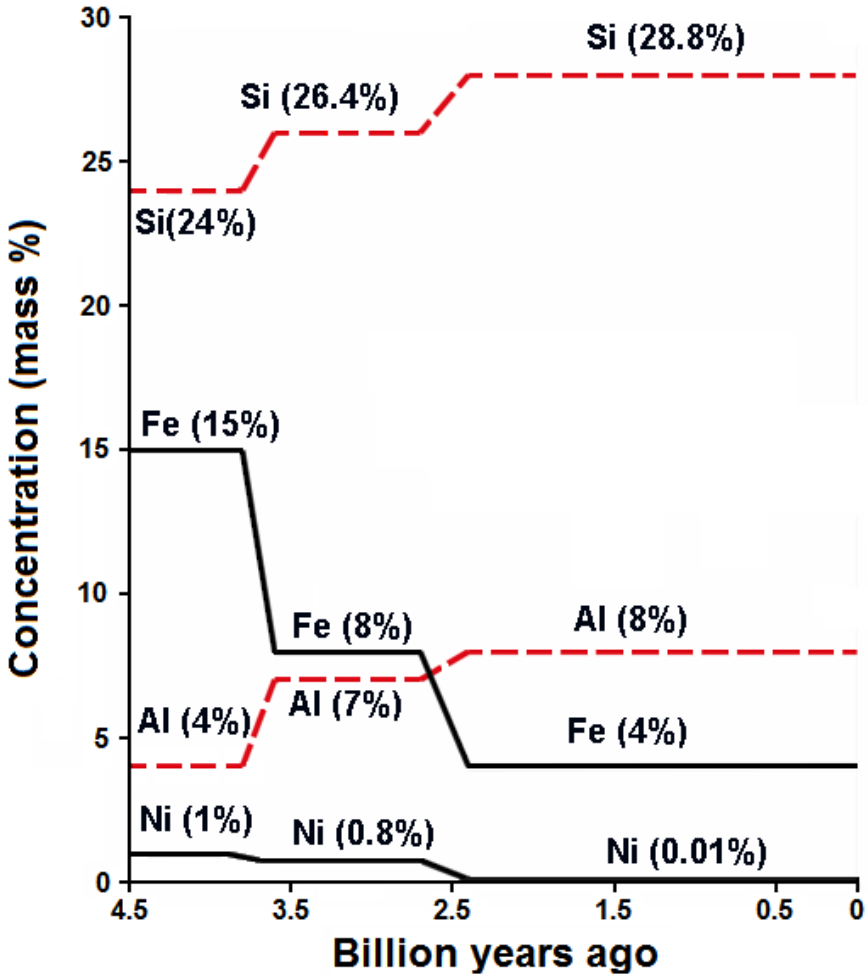

Figure 1. Estimated changes in the concentrations of Fe, Ni, Al, and Si in the Earth's Crust during tectonic plate formation (3.8 Gyr ago) and during the most severe tectonic activity (2.5 Gyr ago).

Successively, between 2.5 and 2.0 Gyr ago, N_2 and O_2 concentrations increased sharply (Great Oxidation Event) in concomitance with the most relevant formation of the Earth's continental crust [18–20]. Thus, a significant coupling appears between the periods of intense tectonic activity and the sudden increments of CO_2 (and H_2O), and later of N_2 and O_2 levels in the atmospheric composition over the Earth's lifetime [1,19,20] (see Figure 2).

The chemical balances underlying the geochemical evolution of the Earth's crust, ocean, and atmosphere can be considered as indirect evidences of recently hypothesized low-energy nuclear reactions (LENR) [27–31], occurring massively in the Earth's crust during periods of intense tectonic activity, and hierarchically organized into two different sets:

$$Fe_{26}, Co_{27}, Ni_{28} \rightarrow Mg_{12}, Al_{13}, Si_{14} \rightarrow C_6, N_7, O_8$$

where the atmospheric elements (C, N, O) can be regarded as results of the second set of reactions, involving Si, Al, and Mg as starting elements. In particular, the estimated Mg increment (3.2%) is equivalent to the Carbon content in the primordial atmosphere (particularly high in the form of CO_2 and CH_4). The second part of reactions (1), involving Mg as starting element and C as resultant, can be regarded as an alternative or a competing mechanism with volcanic degassing [11–15] by which tectonic forces added CO_2 to the atmosphere toward the end of the Hadean period [30,31].

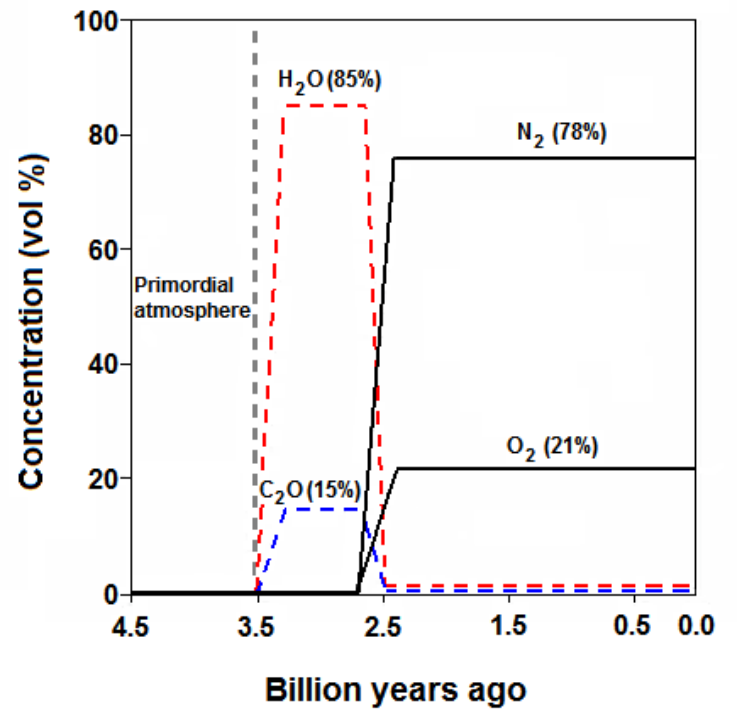

Figure 2. Variation in the atmospheric composition over the Earth's life time. During the Archean era, about 15% of the Earth's atmosphere was constituted by Carbon Dioxide (CO_2), and the remaining part was mainly composed by Water Vapor (H_2O).

Some quantitative considerations and experimental evidences can be advanced to support this hypothesis. First, assuming a mean density equal to 3.6 g/cm^3 and a thickness of ~60 km of the Earth protocrust, the mass increase in Mg (~3.5×10^{21} kg, corresponding to 3.2% of the mass of protocrust involved in the reaction), and therefore in C, implies a very high atmospheric pressure. Given a terrestrial surface area of 5.1×10^{14} m^2 and considering the same gravitational acceleration for the proto-Earth, we obtain an atmospheric pressure of 660.70 atm. This very high value, plausible and consistent with the conditions prevailing between 3.8 and 2.5 Gyr ago, is corroborated by models presented for a CO_2 and CH_4-rich primordial atmosphere with ground level pressures of some hundred atm (~650 atm, as was the value reported in [1]).

Furthermore, significant neutron emissions have been measured both at the Earth's crust scale during earthquakes preparation stages (Figure 3) [32–35] and at the laboratory scale during crushing tests on non-radioactive rock specimens.

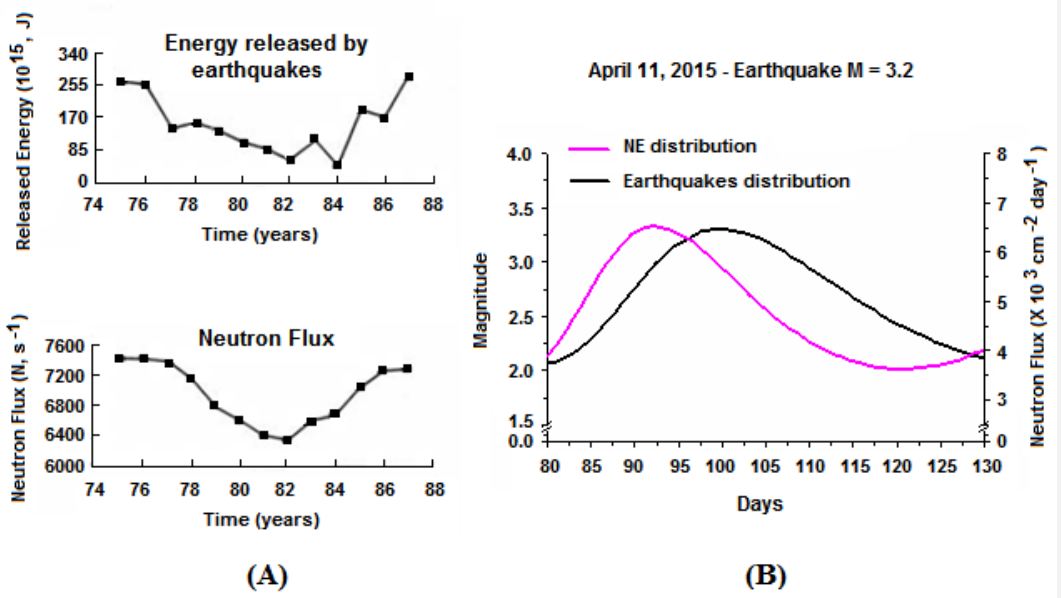

Figure 3. (**A**) Seismic activity and neutron flux measurements in the period 1975–1987, Kola Peninsula, Russia [32]); (**B**) Typical time correlation between fitting distributions of neutron flux measurements at the Murisengo gypsum mine, and a local seismic swarm (magnitude 3.2 main shock) [35] (**B**).

During the laboratory experiments, neutron and other forms of energy emissions have been measured in correspondence to micro- and macro-fracturing [36–40], with final considerable reduction in the Fe content consistently counterbalanced by an increase in Al, Si and Mg contents [27–29]. A further evidence supporting the link between seismicity and variations in the atmospheric CO_2 is the spatial organization of CO_2 release from the ground in the Nepal Himalayas, apparently controlled by large earthquakes [41].

2. Atmospheric CO_2 and the Carbon Cycle

Carbon dioxide is an integral part of the carbon cycle, in which carbon is exchanged between the Earth's oceans, soil, rocks, and the biosphere at two different rates: the slow carbon cycle, involving geochemical processes between the atmosphere, oceans, soil, rocks and volcanism, and the fast carbon cycle, which refers to movements of carbon between the environment and living organisms in the biosphere, including photosynthesis and respiration [42]. The slow-rate geochemical processes, including the formation and burial of carbonates, the burial of organic matter (on land or in the ocean), and the volcanism have largely determined the flow of CO_2 into and out of the atmosphere on multimillion-year time scales. As currently accepted, the reduction of atmospheric CO_2 caused by these burial processes appears to be bound by tectonic processes, which return the carbon from the Earth's mantle and crust to the atmosphere through volcanism degassing (less frequent as earth mantle progressively cooled). Later, the flow of atmospheric CO_2 began to be controlled by other natural processes such as the origin and the expansion of forests, which caused increased burial of organic carbon by photosynthesis, and the respiration of living organisms, which added back CO_2 to the atmosphere [43,44].

In the pre-industrial era, the flow of atmospheric CO_2 was considered to be largely in balance, with natural sources nearly balanced by natural CO_2 sinks. Since the Industrial Revolution, the anthropic activity has perturbed the carbon cycle directly adding carbon to the atmosphere from burning fossil fuels and land-use changes (mainly deforestation). According to the carbon cycle

models [45], about 57% of the anthropogenic CO_2 emissions should be removed from the atmosphere by the biosphere (vegetation and land) and oceans, which behave as carbon sinks.

As current atmospheric CO_2 levels exceed measurements from the last 1000 years and are rising quickly, anthropogenic perturbation of the global carbon cycle is considered to be the only responsible for causing the dramatic increase in CO_2 of the contemporary Earth's atmosphere [46,47]. In accordance with this paradigm, the global carbon budget describing the exchanges of CO_2 between the atmosphere and the other major carbon reservoirs is currently given by the following balance equation:

$$\text{atm growth} = \text{fossil fuel} + \text{land use change} - \text{ocean sink} - \text{land sink}$$

where geochemical terms are usually neglected, as their rate is considered too slow to have some relevance on the atmospheric CO_2 concentration over hundred- or thousand-year timescales, or because they became relatively infrequent, like volcanism. However, some doubts remain regarding that balance, since the ocean sink is estimated by a combination of global ocean biogeochemistry models and the land sink is often estimated from the residual of the other budget terms [47]. With regard to the latter point, recent studies suggest that the role of tropical forests may have been yet very poorly quantified, indicating a terrestrial tropical carbon sink larger than the usual estimates [48,49]. Accounting for this finding while balancing the global carbon cycle implies that the currently considered carbon sources are larger [50], and/or the existence of other carbon sources to be considered in the budget.

3. Data Analysis

Observing the relationship between the anthropogenic CO_2 emissions and the atmospheric CO_2 growth rate (compare diagrams in Figure 4A,C) plotted in Gt C year^{-1} from 1955 to 2013 (the choice of the period is motivated by the need for comprehensive and reliable data), some evidences may cast some doubts on the fact that anthropogenic emissions effectively drive all the atmospheric CO_2 growth [51–53]:

- the significant acceleration in the anthropogenic emission rate, largely due to China's contribution, observed since 2002 and not reflected in an analogous trend of atmospheric CO_2, which yet continued its steady growth;
- the downward trend of atmospheric CO_2 in some periods, especially from 1988 to 1993, despite the continuous growth of the anthropogenic emissions;
- the intensive cyclic fluctuations around the trend line in the atmospheric CO_2 growth rate in spite of the smoother increase in the anthropogenic CO_2 emission rate.

Consistently with neutron emissions observed in correspondence to fracturing at laboratory and Earth's scales, the hypothesized LENR related to neutron emissions from active faults may be regarded as the principal cause of magnesium depletion and the consequent carbon formation and degassing of freshly formed CO_2 during seismic activity. In this way, it is worth investigating the possible relationship between the atmospheric CO_2 growth rate and the global seismic-moment release rate (Nm year^{-1}, newton-metres per year).

The seismic moment M measures the size and the energy of an earthquake according to the definition, $M = \mu A \delta$, where μ is the shear modulus of the rock in which the fault is embedded, A is the area of the fault break, and δ is the mean displacement across the fault during the earthquake. M thus has dimension of torque (Nm) [54].

Therefore, a comparison among the rates of anthropogenic CO_2 emission, global seismic-moment release, and atmospheric CO_2 growth shows that all the considered time series show an upward trend, linear for atmospheric and anthropogenic data, quadratic for seismic data instead (diagrams of Figure 4A–C).

Commento [M4]: Please confirm if the revised is correct or not?

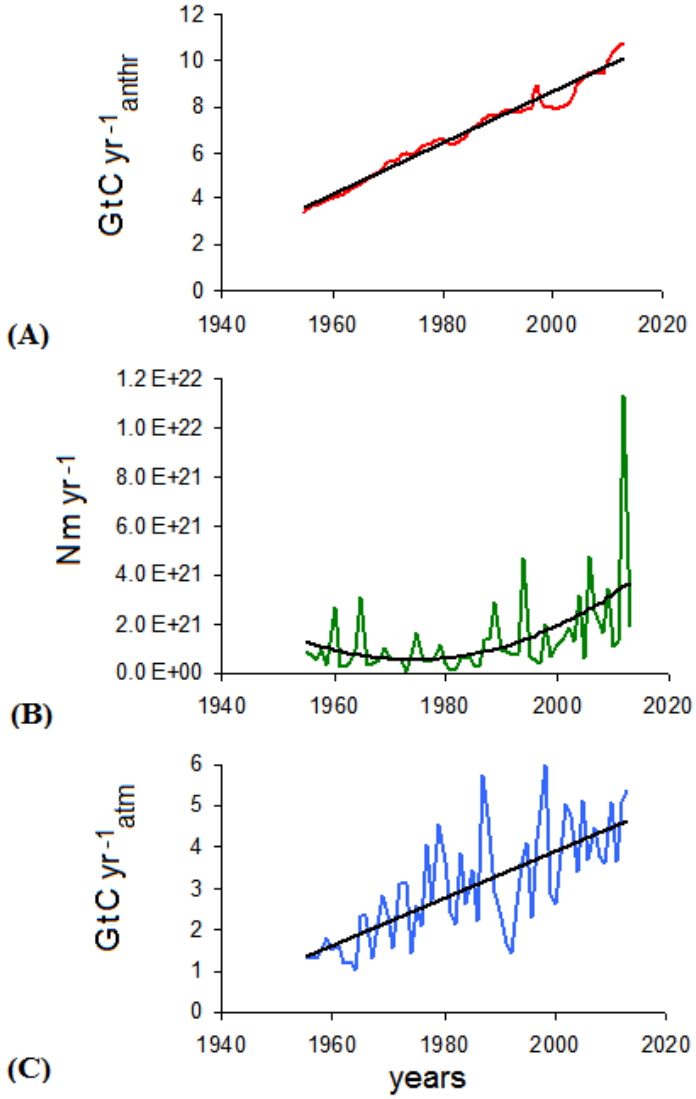

Figure 4. (**A**) Time series plots (1955–2013) of annual anthropogenic CO_2 emissions; (**B**) Global seismic-moment release; (**C**) Atmospheric CO_2 growth rate (C) with trend lines in black.

However, it is worth noting that anthropogenic CO_2 emissions exhibit low-amplitude fluctuations when compared to those of the atmospheric CO_2 growth rate (compare Figure 4A,C), i.e., up to one order of magnitude smaller considering peak-to-peak excursions.

A further remark results considering the periodicities hidden in the fluctuations of the time series. The FFT analysis of residual data, obtained by subtracting the trend component from the actual data, shows that the low-frequency components (approximately lying in the 0–0.15 year $^{-1}$ interval) in the anthropogenic emission spectrum prevails over higher frequencies, unlike more uniform mixture of components in seismic-moment release and atmospheric CO_2 spectra, where spectral peaks appear at high frequencies as well (compare FFT diagrams of Figure 5).

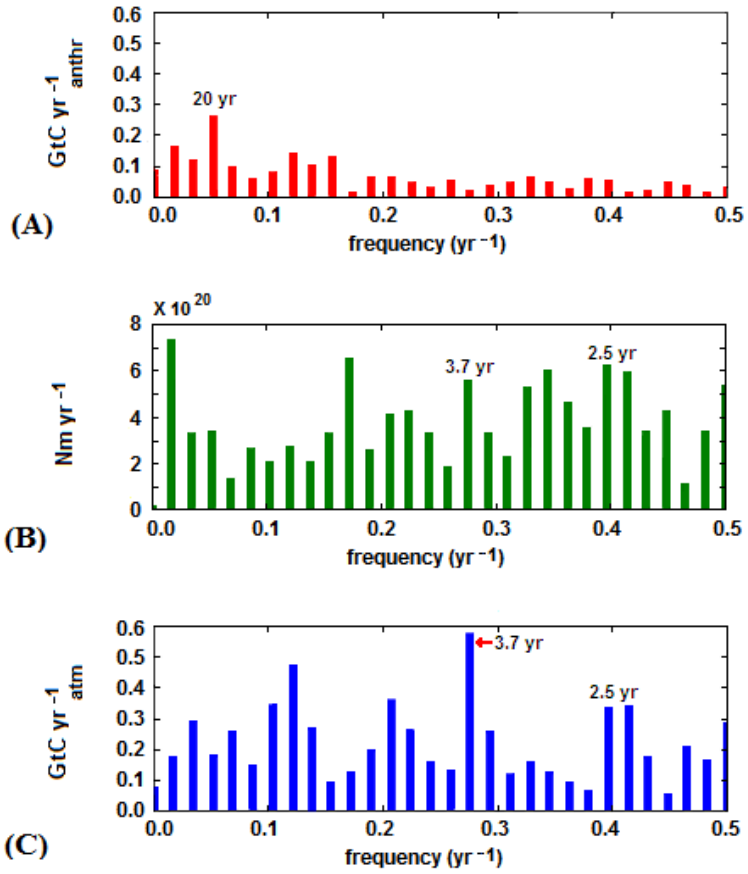

Figure 5. (**A**) FFT spectra of the de-trended time series: anthropogenic CO_2 emissions; (**B**) Global seismic-moment release; (**C**) atmospheric CO_2 growth rate. Note: the discrepancy between the main peaks of anthropogenic (20 year) and atmospheric (3.7 year) spectra; the peaks shared, e.g., at 2.5 and 3.7 years, by seismic and atmospheric spectra.

As shown in Figure 5A, the anthropogenic time series exhibits a dominant spectral peak at 0.05 year^{-1}, equivalent to a 20-year period which results to be uncorrelated with atmospheric CO_2 fluctuations, since this periodicity is not relevant in the atmospheric spectrum (observe the fourth spectral component of atmospheric CO_2 data in Figure 5C). Conversely, atmospheric fluctuations exhibit a main periodicity of 3.7 year, almost absent in the anthropogenic emission spectrum. This discrepancy looses partly the bond between anthropogenic emissions and atmospheric CO_2 growth rate.

Instead, the 3.7-year periodicity is relevant both in atmospheric CO_2 and in seismic-moment spectra, as well as other periodicities like spectral peaks at approximately 2.5 years (see Figure 5B,C). Actually, these periodicities are almost absent in the anthropogenic time series, as if the fluctuations in the atmospheric CO_2 growth were preferably driven by the seismic activity rather than by the anthropogenic causes.

4. Conclusions

The presented results derive from geochemical studies on the chemical evolution at the Earth's scale that affected Mantle, Crust, and Atmosphere during the periods of the most severe tectonic activity, corroborated by experimental evidences of neutron emissions during rock fracture with concomitant changes in the elements concentration of the specimens.

It is important to observe how the conventional assumptions of chemical elements' migration do not imply the nearly perfect satisfaction of the mass balances, whereas the chemical balances among the most abundant elements derived from geochemical data are considered as indirect evidences of conjectured LENR reactions. The atmospheric elements (C, N, O) can be regarded as results of a set of reactions, involving Si, Al, and Mg as starting elements, massively triggered by tectonic activity. In particular, this conjecture not only accounts for atmospheric CO_2 formation and its variations over the Earth's life time, but could provide an explanation also to some observed anomalies in the correlation between the atmospheric CO_2 growth and the anthropogenic emission rates.

By examination of the time series, fluctuations of the atmospheric CO_2 growth rate cannot be explained in terms of low-amplitude anthropogenic emission fluctuations (nearly an order-of-magnitude difference). Furthermore, the main periodicities of these two phenomena are different.

Although variations in climate variables are recognized as important drivers of the interannual variability of the atmospheric CO_2 growth rate [55], the present relationship between atmospheric and seismic variables appears to be rather robust during the last 50 years, and provides a new diagnostic tool for better understanding of the global carbon cycle.

In conclusion, the time series analysis demonstrates the trending behavior of atmospheric CO_2 growth rate in response to the anthropogenic emissions, whereas, in the light of LENR, atmospheric CO_2 fluctuations can be ascribed to the cycles of the worldwide seismicity.

Supplementary Materials: Earthquake data are available online at https://earthquake.usgs.gov/earthquakes/search/. CO_2 emission data are available online at http://www.globalcarbonproject.org/carbonbudget/archive.htm#CB20147.

Commento [M5]: Please mention it in main text.

Author Contributions: conceptualization, writing—review and supervision A.C..; investigation, data curation, formal analysis, writing—original draft preparation G.N.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Liu, L. The inception of the oceans and CO_2-atmosphere in the early history of the Earth. *Earth Planet. Sci Lett* **2004**, *227*, 179–184.
2. Weast, R. C., *Handbook of Chemistry and Physics*, *CRC Handbook of Chemistry and Physics*; CRC Press: New York; 1980.
3. Garrison, T.S., *Oceanography: an invitation to marine science*; Thompson Brooks Cole: Belmont; 2005.
4. Schopf, J., *Earth's earliest biosphere: its origin and evolution*; Princeton University Press: Princeton; 1983.
5. Kolb, E., *Blind watchers of the sky: the people and ideas that shaped our view of the universe*; Oxford University Press: Oxford; 2000.
6. Kolb, E. et al. http://arXiv:hep-th/0503117v1, 2005.
7. Williams, R.P.; Da Silva, F.J.R. Evolution was chemically constrained. *J Theor Biol* **2003**, *220*, 323–343.
8. Buesseler, K.O. et al. Ocean iron fertilization moving forward in a sea of uncertainty. *Science* **2008**, *319*, 162.
9. Holland, H.D. The oxygenation of the atmosphere and oceans. *Philos Trans R Soc Lond Ser B* **2006**, *361*, 903–915.
10. Abbott, D.H. et al. An empirical thermal history of the Earth's upper mantle. *J Geophys Res* **1994**, *99(13)*, 835–850.
11. Kasting, J.F.; Ackerman, T.P. Climatic consequences of very high carbon dioxide levels in the Earth's early atmosphere. *Science* **1986**, *234*, 1383–1385

12. Yung, Y.L.; De More, W.B. *Photochemistry of planetary atmospheres*; Oxford University Press: New York; 1999.
13. Ahrens, T.J. The state of mantle minerals. *Technophysics* **1971**, *XX*, 189–219.
14. Ringwood, A.E. The chemical composition and the origin of Earth. In *Advance in earth science*; P.M. Hurley, Ed. ; MIT PRESS: Cambridge, 1962.
15. Gaillard, F.; Scaillet, B. A theoretical framework for volcanic degassing chemistry in a comparative planetology perspective and implications for planetary atmospheres. *Earth Planet Sci Lett* **2014**, *403*, 307–316.
16. Tera, F.; Papanastassiou, D.A.; Wasserburg, G.J. Isotopic evidence for a terminal lunar cataclysm. *Earth Planet Sci Lett* **1974**, *22*, 1–21.
17. Cohen, B.A.; Swindle, T.D.; Kring, D.A. Support for the Lunar Cataclysm Hypothesis from Lunar Meteorite Impact Melt Ages. *Science* **2000**, *290*, 1754–1755.
18. Saito, M.A. Less nickel for more oxygen. *Nature* **2009**, *458*, 714–715.
19. Kopp, R.E. et al. The Paleoproterozoic snowball Earth: A climate disaster triggered by the evolution of oxygenic photosynthesis. Proc Nat Acad Sci Un St Am, 2005, Vol. 102, 11131–6.
20. Konhauser, K.O. et al. Oceanic nickel depletion and a methanogen famine before the Great Oxidation Event. *Nature* **2009**, *458*, 750–753.
21. Favero, G.; Jobstraibizer, P. The distribution of aluminum in the Earth: from cosmogenesis to Sial evolution. *Coord Chem Rev* **1996**, *149*, 367–400.
22. Taylo, S.R.; McLennan, S.J., *Planetary Crusts: their composition, origin and evolution*; Cambridge University Press: Cambridge; 2009.
23. Hawkesworth, C.I.; Kemp, A.I.S. Evolution of the continental crust. *Nature* **2006**, *443*, 811–817.
24. Doglioni, C. Interno della Terra. In *Enciclopedia Scienza e Tecnica;* Treccani, 2007; pp. 595–605.
25. Rudnik, R.L.; Fountain, D.M. Nature and composition of the continental crust: a lower crustal perspective. *Rev Geophys* **1995**, *33(3)*, 267–309.
26. Yaroshevsky, A.A. Abundances of chemical elements in the Earth's crust. *Geochem Int* **2006**, *44(1)*, 54–62.
27. Carpinteri, A. et al. Neutron emissions in brittle rocks during compression tests: monotonic vs. cyclic loading. *Phys Mesomech* **2010**, *13*, 264–274.
28. Carpinteri, A.; Manuello, A. Geomechanical and geochemical evidence of piezonuclear fission reactions in the Earth's crust. *Strain* **2011**, *47*, 282–292.
29. Carpinteri, A. et al. Piezonuclear fission reactions: evidences from microchemical analysis, neutron emission, and geological transformation. *Rock Mech Rock Eng* **2012**, *45*, 445–459.
30. Carpinteri, A.; Manuello, A.; Negri, L. Chemical evolution in the Earth's mantle and its explanation based on piezonuclear fission reactions. In *Acoustic, Electromagnetic, Neutron Emissions from Fracture and Earthquakes*; A. Carpinteri, G. Lacidogna, A. Manuello, Eds.; Springer: Switzerland, 2015.
31. Carpinteri, A.; Manuello, A. Evolution and fate of chemical elements in the Earth's Crust, Ocean, and Atmosphere. In *Acoustic, Electromagnetic, Neutron Emissions from Fracture and Earthquakes*; A. Carpinteri, G. Lacidogna, A. Manuello, Eds.; Springer: Switzerland, 2015.
32. Sobolev, G.A.; Shestopalov, I.P.; Kharin, E.P. Implications of Solar Flares for the Seismic Activity of the Earth. Izvestiya. *Phys. Solid Earth* **1998**, *34*, 603–607.
33. Volodichev, N.N. et al. Lunar periodicity of the neutron radiation burst and seismic activity on the Earth, Proc. of the 26th International Cosmic Ray Conference, Salt Lake City, 17-25 August 1999.
34. Sigaeva, E. et al. Thermal neutrons' observations before the Sumatra earthquake. *Geophysical Research Abstracts* **2006**, *8*, 00435.
35. Carpinteri, A.; Borla, O. Fracto-emissions as seismic precursors. *Engineering Fracture Mechanics* **2017**, *177*, 239-250.
36. Carpinteri, A. et al. Time correlation between acoustic, electromagnetic and neutron emissions in rocks under compression, Proc. Conference & Exposition on Experimental and Applied Mechanics (SEM), Costa Mesa, California, USA, 2012, CD-ROM, Chapter N. 50, pp. 387-393.
37. Carpinteri, A. et al. Electromagnetic and neutron emissions from brittle rocks failure: experimental evidence and geological implications. *Sadhana* **2012**, *37*, 59–78.
38. 38. O. Borla et al., Electromagnetic emission as failure precursor phenomenon for seismic activity monitoring, *Proc. Conference & Exposition on Experimental and Applied Mechanics (SEM)*, Greenville, South Carolina, USA, 2014, Vol. 5, pp. 221–229.

39. Lacidogna, G. et al. Correlation between acoustic and other forms of Energy emissions from fracture phenomena. In *Acoustic, Electromagnetic, Neutron Emissions from Fracture and Earthquakes*; A. Carpinteri, G. Lacidogna, A. Manuello, Eds.; Springer: Switzerland, 2015.
40. Manuello, A. et al. Neutron emissions and compositional changes at the compression failure of Iron-rich natural rocks. In *Acoustic, Electromagnetic, Neutron Emissions from Fracture and Earthquakes*; A. Carpinteri, G. Lacidogna, A. Manuello, Eds.; Springer: Switzerland, 2015.
41. Girault, F. et al. Large-scale organization of carbon dioxide discharge in the Nepal Himalayas. *Geophys Res Lett* **2014**, *41*, 6358–6366.
42. Rothman, D.H. Atmospheric carbon dioxide levels for the last 500 million years, Proc Natl Acad Sci USA, 2001, 99, 4167–4171.
43. Royer, D.L. Atmospheric CO_2 and O_2 during the Phanerozoic: tools, patterns, and impacts. In *Treatise on Geochemistry*, K. Turekian, H. Holland, Eds.; Elsevier Science, 2014; pp.251–267.
44. Bergman, R.A. et al. Copse: a new model of biogeochemical cycling over Phanerozoic time. *Am J Sci* **2004**, *301*, 182–204.
45. 45. http://cdiac.ornl.gov/trends/emis/tre_glob_2013.html, CDIAC, 2016: Global Fossil-Fuel CO_2 Emissions.
46. 46. http://www.globalcarbonproject.org/carbonbudget/
47. 47. IPPC - Intergovernmental Panel on Climate Change, AR4-WG1.
48. Lewis, S.L. et al. Increasing carbon storage in intact African tropical forests. *Nature* **2009**, *457*, 1003-1006.
49. Tollefson, J. Counting carbon in the Amazon. *Nature* **2009**, *461*, 1048–1052.
50. Schuur, E.A.G. et al. The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature* **2009**, ***459***, 556–559.
51. Salby, M.L., *Physics of the Atmosphere and Climate*; Cambridge University Press: Cambridge, 2012.
52. Oliver, J.G.J. Trends in global CO_2 emissions: 2015 Report. PBL Netherlands Environmental Assessment Agency, 2015.
53. Courtney, R.S. Limits to existing quantitative understanding of past, present and future changes to atmospheric carbon dioxide concentration, International Conference on Climate Change, New York, 2008.
54. 54. D.L. Turcotte, *Fractals and Chaos innGeology and Geophysics* (Cambridge University Press, Cambridge, 1997).
55. Keeling, C.D. et al. Interannual extremes in the rate of atmospheric carbon dioxide since 1980. *Nature* **1995**, *375 (6533)*, 666–670.