Earth, Moon, and Planets (2006) 98: 291–297
DOI 10.1007/s11038-006-9092-8

8. A Synthetic Interdisciplinary "Chronological Frieze": an Attempt

DIDIER DESPOIS and MURIEL GARGAUD
Observatoire Aquitain des Sciences de l'Univers, Université Bordeaux 1, Bordeaux, France
(E-mail: despois@obs.u-bordeaux1.fr, gargaud@obs.u-bordeaux1.fr)

(Received 1 February 2006; Accepted 4 April 2006)

Abstract. This chapter introduces the chronological and interdisciplinary "frieze" which presents the main events relevant (in our opinion) to the problem of the emergence of life on Earth. This selection of events is directly connected to the previous chapters of this book.

Keywords: Origin of life, chronology, time scales, hadean, archean, proterozoic

8.1. General Description

The frieze enclosed at the end of this book (Figure 8.1) presents a table of various events considered by the authors as relevant to the origins of life on Earth. These events have been tentatively chronologically ordered in accordance with actual knowledge within all the scientific disciplines involved in astrobiology.

When isotopic dating is available, as is the case for most geological events or processes as well as for some astronomical events, an absolute age is obtained which corresponds to the time elapsed between the event and present. For other astronomical events or processes, durations or time intervals are estimated either from theoretical models or observational arguments. In all cases time can be expressed either with respect to present (BP) or with respect to a reference time, t_0[1]. A separate timescale, starting at (t_0*)[2], has however been introduced for the early phases of the Sun formation, due to the present uncertainty on the precise timing of these events with respect to planetary formation. In other cases (prebiotic chemistry and early biological evolution) when the dating remains relative, the chronology is qualitatively presented as a logical sequence of events (taking into consideration that this sequence is not unique).

[1] t_0 corresponds to the age of the oldest solids in the Solar System which have been dated until now

[2] t_0* is defined as the beginning of the collapse of the interstellar cloud core which gave birth to the Solar System

In our initial project, it was considered to give a rough estimate of the duration of events or reactions for chemical and early biological processes; such a target rapidly appeared inaccessible as it consists in an extremely complex or even impossible task. The only possibility consisted in establishing some time-beacons. The opportunity to assign an absolute age (by radiochronology) to an indisputable microfossil identified in a sedimentary sequence constitutes a reliable time marker for biological evolution. Unfortunately, such absolute markers remain so far extremely sporadic, and in their absence only a relative succession of biological events can be suggested (even if still hotly debated).

An attempt was made to systematically refer to all available data sources and in case of controversies, to present alternative models and views and to cite the appropriate references. Unfortunately, this was not always possible: for example, too many scenarios are currently proposed for prebiotic chemistry and early biological evolution; likewise dating of the "first" microfossils is subject to many controversies impossible to report in a synthetic form.

As already discussed in the previous chapters, this "*chronological frieze*" does not present a complete overview of the Earth evolution but rather is limited to the period ranging between t_0* and the so-called explosion of life at the beginning of the Cambrian period. The selected period includes three geological eras: the Hadean, Archaean and Proterozoic, which are classically regrouped under the Precambrian. The fact that the Precambrian is the period during which the most important events relative to the emergence and early evolution of life took place justifies our selection.

The data inserted in the "chronological frieze" were subject to long interdisciplinary discussions in order to resolve the constraints linked to the different types of chronometers used by each discipline concerned with the origins of life. When possible an interpretation relevant for the origin of life is proposed, and tentatively inserted in an unique and coherent interdisciplinary timescale. This theoretical *modus operandi* is limited due to the huge lack of chronological data relative to prebiotic and early biological evolution, which did not permit their insertion into a reliable time scale. Consequently, it was decided to insert the part of the "chronological frieze" relative to the prebiotic chemistry and early biological evolution between 4.4 and 2.7 Ga. The date of 3.8 Ga was chosen because it represents the age of the oldest sedimentary rocks so far recognized.

Whatever the dating method is, age is determined within an uncertainty domain; consequently, when available, an error bar on the date/age is given. It must be noted that this error bar gives the analytical uncertainty on age determination, and is totally independent of the interpretation of the age. For instance, in an old magmatic rock, the age measured on a zircon crystal can reflect the age of the source of the magma, the age of magma crystallization or even the age of a subsequent thermal event (called metamorphism). The discussion relative to these aspects is presented in a column called "reliability." In some critical cases, discussion has been extended further as "notes."

8.2. How to Interpret the Data of the "Chronological Frieze"?

8.2.1. Eon and phase

Eon and phase refer to periods of time. Eons are officially defined by the International Union of Geological Sciences (IUGS). However, since Hadean is not official in the latest version of the international stratigraphic chart, it was decided to place the Hadean–Archaean boundary at 4.0 Ga, which is roughly the age of the oldest known rocks. In addition to this official international nomenclature, Earth history is subdivided in several phases, which refer to periods important in terms of life apparition and development; these phases are closely related to the various chapters of this book.

8.2.2. Age, error bars, time and duration

They are expressed in mega years (Ma or Myr) or giga years (Ga or Gyr). The choice of "anno" or "year" reflects the convention differences between scientific domains: Geology and Astronomy respectively. Ages refer to present time, and are thus expressed as "age before present" (BP), more precisely defined as 1950 AD(see chapter 1).

8.2.3. Reference times

Excepted for the formation of the Sun, and to some extent, for the formation of the protoplanetary disk, all relative times presented in the "chronological frieze" refer to an absolute time t_0, that corresponds to the oldest solids in the Solar System which have been dated until now; these solid particles are the CAIs (Calcium–Aluminium Inclusions) of the Allende meteorite, dated at 4.5685 Ga BP. For the first 1–10 Myr, corresponding to the stellar formation and early protoplanetary evolution, a t_0* time has been introduced, arbitrarily chosen as the start of the collapse of the initial molecular cloud core. This t_0* time can be linked to the absolute time t_0 if the durations of the various stellar successive phases (e.g. protostar, T Tauri) are estimated; it must be clear that these durations are model-dependent.

8.2.4. Events

The column "events" lists what we consider the most relevant phenomenons for our understanding of emergence of life. They are presented under a generic title. In case of complex events made of a succession of composite steps, the column labelled "Comments about these events" attempts to describe these different steps as clearly as possible. Their importance or their role in the emergence of life is presented in the column "Consequences for life."

8.2.5. Dating methods

The tools used to determine the age of an event are reported in this column. Chapter 2 provides additional information about methods.

8.2.6. Relevant observations

This column gives additional information about the dated objects, the nature of observations, and/or the model used.

8.2.7. Reliability

This column reports the problems linked to the data interpretation. In some cases, it points to the vivid controversies in the scientific community.

8.2.8. Consequences for life's origin and evolution

This column attemps to present the potential or possible link between a particular event and the emergence of life.

8.2.9. References

Only the number of the relevant chapter of this book is reported here; detailed references can be found in the chapter itself.

8.2.10. Notes

They refer to the following further details on data interpretation and possible controversies:

(#N1) t_0* must be distinguished from t_0, which is the age of the oldest dated sample of primitive material in the solar system (see below: CAIs, dated 4.568 ± 1 Gyr).

(#N2) The date corresponding to t_0 (4568.5 Ma BP) is now rather well established : (1) Amelin (2002) and Bouvier et al. (2005) show that Allende CAI ages are consistent with this age within an error bar of ±0.4 Ma (2)

Lugmair and Shukolyukov (1998) get the same age by adding Pb–Pb age of Ste Marguerite (H4) with ^{26}Al–^{26}Mg age (3) The same age is obtained if we add the Pb–Pb age of 6 angrites (Baker et al., 2005) and the ^{26}Al–^{26}Mg internal isochrone age of 99555 (their total rocky age are obviously 1.2 Ma too old)

(#N3) Hence possible role in the existence of Europa-like bodies

(#N4) A last metal-silicate equilibrium is recorded at 30 Ma with an error bar 11–50 Ma. Moreover N-body models predict a rather rapid first phase in telluric planet formation up to (roughly) the size of Mars ("planetary embryos") followed by a slower one (build up of Earth-size bodies by embryo encounters). The age of 30 Ma for the Earth could correspond to a collision with a Mars size body and indeed, a recent work propose an ^{182}Hf–^{182}W age of 45 Ma for the Moon crustal differentiation, which could correspond to the end of magmatic oceans on the Moon.

(#N5) The magmatic ocean stage could have lasted longer on Earth than on Moon, may be 60–70 Ma (^{129}I–^{129}Xe chronometers coupled to ^{129}I–^{129}Xe). The different ^{142}Nd isotopic anomalies between chondrites and the Earth (Boyet and Carlson, 2005) show that the effective formation of Earth magmatic ocean was achieved 30 Ma after accretion. In addition, due to their different gravities, less plagioclase crystallized in Earth magma ocean when compared to Moon where plagioclase accumulation formed the anorthositic crust.

(#N6) Before this shock, a H_2-rich primitive atmosphere may have existed; it subsequently disappeared by hydrodynamic escape or as the consequence of impacts.

(#N7) 100 Ma correspond to the epoch at which the atmosphere begins to retain ^{129}Xe produced from ^{129}I. However the atmosphere may have stayed open during a much longer period (in order to allow the escape of the ^{136}Xe produced by ^{244}Pu radioactivity). About 100 Ma is only an average closure time, because of problems linked to the measure of the age of reservoirs.

(#N8)The isotopic systems ^{146}Sm–^{142}Nd et ^{244}Pu–^{136}Xe indicate a very active Earth during the Hadean, allowing for a global differentiation during the first 100–400 Ma. The oldest dated zircon (4.4 Ga) does not have high $\delta\ ^{18}$O typical of interaction with water at low temperature. This $\delta\ ^{18}$O alone, could be interpreted as mantle value, however, zircon crystal also contains quartz and plagioclase inclusions; which demonstrates that it crystallized in a continental crustal magmatic rock.

(#N9) Other authors consider that most, if not all, halogens and H, C, N, O, S, P, were already present and available on Earth surface at 4.4 Ga when first oceans formed.

(#N10) On Earth this episode is not certain but only extremely probable; indeed, on the Moon, the Imbrian event is recognized only on the visible face of the Moon (which could then be considered as a local event)

(#N11)A similar isotopic deviation can be produced abiotically. The sedimentary nature of the graphite was analysed, and even its age has been questioned.

(#N12) It is impossible to say whether these metabolisms appeared simultaneously or successively. A parallel evolution appears possible, and even supported (e.g. phylogenetic radiation within the bacteria and prior divergence of the archaea) for most respiration types, photosynthesis and methanogenesis.

(#N13) The interpretation of these observations is strongly debated. If macroscopic laminar structures do correspond to fossil stromatolites, this would prove the occurrence of laminated microbial communities (microbial mats) implying the presence of metabolically diverse microorganisms. If the presence of microfossils associated to these structures is confirmed, it would constitute evidence for the existence of cellular life. If negative $\delta\ ^{13}C$ values are actually biogenic and syngenetic with the rock, some type of autotrophic metabolism (photosynthesis and/or chemoautotrophy) would have already developed.

(#N14) Eukaryotic morphologies characterized by extent surface decoration are widely accepted

The frieze may be found in print as an insert at the back of the print publication. This supplementary material is also available in the online version of this article at http://dx.doi.org/10.1007/s11038-006-9092-8 and is accesssible for authorized users.

Acknowledgements

We'd like to thank warmly all the authors for their help during the "making of" of this "chronological frieze." We are especially very grateful to the coordinators of the various chapters of this review for fruitfull discussions, comments and critical reading of the (numerous) "proto-frieze" which precede this one: Philippe Claeys, Purification Lopez-Garcia, Hervé Martin, Thierry Montmerle, Robert Pascal and Jacques Reisse. We also thank especially Francis Albarede, Daniele Pinti and Franck Selsis for fruitfull discussions on oldest dated sample, oceans and atmosphere formation. Finally, we also thank Judith Pargamin for her help in the editorial presentation of this frieze and Michel Viso for his constant support to this project.

References

Amelin Y., Grossman L., Krot A. N., Pestaj T., Simon S. B., and Ulyanov A. A. (2002), *Lunar and Planetary Institute Conference Abstracts* **33**, 1151.

Baker, J., Bizzarro, M., Wittig, N., Connelly, J., and Haack, H.: 2005, *Nature* **436**, 1127–1131.

Bouvier, A., Blichert-Toft, J., Vervoort, J. D., McClelland, W., and Albarede, F.: 2005, *Geochim. Cosmochim. Acta* **69**(Suppl.), 384 .

Boyet, M. and Carlson, R. W.: 2005, *Science* **309**, 576–581.

Lugmair, G. W. and Shukolyukov, A.: 1998, *Geochim. Cosmochim. Acta* **62**, 2863–2886.