Ciências da Terra (UNL)	Lisboa	Nº 18	pp. 105-110	2013

Stratigraphy – The basis for any climate reconstruction

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Summary

Environmental reconstruction is one of the fundamental objectives of Geology. Climate development is particularly significant since Lithosphere, Hydrosphere (+ Cryosphere), Atmosphere and Biosphere interact modeling in time the characteristics of each one. This contribution reviews the fundamentals that have allowed climate reconstruction from scales of millions to tens of years, integrating ocean and continental records defined in sediment and ice cores as well as in other archives (speleothemes, corals tree-rings, etc). The degree of accuracy is inherent to the age of the archive and to attain precision in dating is a major challenge for this area of Science. Here we add some reflections on dating techniques and their significance.

***Keywords*:** Climate reconstructions, proxies, archives, time-scales, Paleo

Any science that has among its objectives the "reconstruction" needs archives to obtain proxies as well as additional elements that allow for a correct dating. Therefore, environmental factors or proxies characterizing environments and age-constrain signals are crucial. The archives in which to find that information are limited. Sedimentary sequences, including lithological, paleontological or geochemical information are certainly what enable a longer record, but not the only ones. Ice cores, stalagmites, tree rings, coral laminations, among others, are also remarkable archives, but limited in time.

In general terms it must be stated that the sedimentary signal observed at any scale is always the result of tectonic and / or climate actions (Vera, 1994). In this context, an important aspect is cyclicity. The sedimentary signal interpreted from different proxies, permitted differentiation of 6 categories (Vail *et al*., 1991; Einsele *et al*., 1991). Cycles from 1st to 3rd order, involving time-intervals longer than one million years, have a clear tectonic component (with obvious repercussion in the ocean and atmosphere dynamics), while the 4th order and shorter have an astronomical origin, orbital or suborbital.

In addition, the range of the signal can be autocyclic or allocyclic depending of their local or global entity, respectively. Consequently, the analysis of the climate signal in the history of our Planet require prior consideration to take into account, on the one hand the age of the study interval, and another the temporary resolution to be worked on. It should be noted that the geological record is highly variable. Aspects such as the conservation of the climate signal are inevitably linked to processes of lithification, taphonomic, etc. The term Paleo implies a reconstruction back in time as such the quality of this type of work depends on the precision of the "age model" constructed for the archive in study. The age error loses importance as we go towards older ages, longer time scales and lower resolution studies. However, high-resolution studies at any geological time implicate higher precision.

Taking into account these considerations, three main groups can be differentiate, according to different time-scales, a quick revision on which those are based on, and the state of the art on each one will follow:

a) Tectonic scale, linked to tecto-eustatic cycles implying factors such as change in the growing of dorsal, orogenic pulses, rising of continents, hotspts or development of new basins. In all these cases are detected changes in the sea-level and the consequent transgresive-regresive pattern (Haq *et al*., 1988; Vail *et al*., 1991). Other relevant aspect is the opening or closures of gateways, allowing paleogeographical modifications affecting water masses dynamics. To determine the amplitude of these cycles and events, among a strict lithological control, it is necessary an age control.

Biostratigraphy offers the possibility to estimate relative ages, ordering strata as well as the opportunity to correlate sections. The organic group to be used is limited both for the age and the characteristic (environment) of sediments. In marine sediments, invertebrates (benthic and nectonics) and mainly microfossils (planktonic and benthic) are regularly used (Murphy & Salvador, 1999).

Additionally, absolute age techniques are used to decipher the chronological framework. Isotopic methods based on the radioactive decay of nuclides species (U-Pb, Rb-Sr, K-Ar, Ar-Ar) offer invaluable information when the mineral composition of the rocks are susceptible to analyze. However, not all rock types and minerals are amenable to isotopic age determination.

Other alternative method is the identification of polarity reversals based on the magnetic property of some minerals and the change in the direction of the remanent magnetization in the rocks. Reversals in the polarity of the Earth's magnetic field are a global signal, well calibrated for the upper Mesozoic and Cenozoic (e.g. Gradstein *et al*., 2004). However, this technique is dependent of other auxiliary such as Biostratigraphy and/or absolute dating.

b) Orbital and Millennial Scale - Orbital variability is originated by variations in the Earth's position relative to the Sun that is, variations in the orbital parameters, eccentricity, obliquity and precession (Berger *et al*. 1989; Berger & Loutre, 1992; Imbrie & Imbrie, 1979). This scale is recorded back to 34 My mainly through expansions and retractions of the global ice volume that occur with periodicities of 400 and 100, 40 and 19-23 ky. The best expression of Earth's climate variability at this scale are the glacial-interglacial cycles that characterize the Quaternary (last 2.6 My) which different lines of evidence have shown to be related to changes in the Earth's orbital elements that affect radiation received at the top of the atmosphere ("insolation") and are a function of hemisphere, latitude, and season (Milankovitch, 1920; Hays, Imbrie & Shackleton, 1976; Berger *et al*., 1993).

Over this orbital-related somewhat smooth record, a higher frequency millennial-scale climate variability consisting of cycles of warmer (*interstadial*) and colder (*stadial*) periods was discovered. This variability, first described in detail in ice core records from Greenland (e.g., Johnsen *et al*., 1992; Grootes & Stuiver, 1997) was later found in climate records all over the world (Voelker *et al*., 2002).

Modeling results point to interactions between slowly evolving components of the climate system (e.g., the ocean and the cryosphere) resulting, for example, in the instability of the oceanic thermohaline circulation to be the source for this climatic variations. The effects of such changes over the land surface are generally mediated by changes in the atmospheric circulation (Ganopolski & Rahmstorf, 2001).

The use of stable isotopes of oxygen is the most common and powerful chemical tool to define stratigraphy for the orbital time scale. It is based on the fact that oxygen (O) occurs in nature with three stable isotopes ^{16}O, ^{17}O and ^{18}O, of which ^{16}O and ^{18}O are the most abundant. The lighter molecules have higher vapor pressure, thus, during evaporation more of the lighter isotopes will be fractionated into vapor while seawater becomes enriched in ^{18}O, the heavier isotope. As the growth of ice caps take more fresh water from the oceans, the remaining seawater becomes more enriched in ^{18}O, what in principle, would affect the isotopic composition of the oceans in the same way everywhere Variations in the ice caps volume are traced by $\delta^{18}O$ measured in the carbonate shells of benthic foraminifera.

$\delta^{18}O$ of a carbonate-containing sample is calculated as:

$\delta^{18}O$ (‰) = $(((O18/O16)_{sample} - (O18/O16)_{standard})/((O18/O16)_{standard}))* 100$

The most common standard is the Vienna Pee Dee belemnite (VPDB).

A compilation of different $\delta^{18}O$ curves from different and widely separated locations of the global ocean allowed for the definition of a stack-standard curve of glacial and interglacial stages. After dating specific events of the standard curve, any $\delta^{18}O$ curve produced anywhere in the ocean could be correlated to the standard curve from which it could obtain its date control points. $\delta^{18}O$ measurements are also very useful for stratigraphic proposes both on ice as well as carbonate continental deposits (speleothems).

Accelerator Mass Spectrometry (AMS) radiocarbon dating is the most precise method of obtaining radiocarbon dates, and has also the advantage of requiring small samples. The ^{14}C is a cosmogenic isotope with a relatively short half-life (5,730 years). The basis for radio carbon dating is that all organisms exchange ^{14}C with the atmosphere (if they are land based) or with water dissolved ^{14}C (if living in water environments). When organisms die, this exchange stops and the ^{14}C in the organisms decays at its half-life. By measuring the content of ^{14}C in a dead organism it is possible to know how long it has been dead.

Radiocarbon dates though need to be calibrated, since the C in the atmosphere depends on solar activity and has fluctuated over time. Ramsey *et al.* (2012) published a record of past atmospheric concentration of ^{14}C based on varved Lake Suigetsu covering the period between 11.2 and 52.8 ky B.P. This new data is a major advance for improving the accuracy with which terrestrial radiocarbon dates can be calibrated that is, converted to calendar time scale. This also allows a direct correlation between other key climate records and the lake record without synchrony assumptions. A more comprehensive understanding of long marine records in their ocean context will also be possible since it will allow the determination of reservoir ages (determinate by different residence times) throughout the covered period.

Tephrochronology is another excellent chronological method based on the dating of ash layers, that is, layers that result from the deposition of the fine fraction of the materials produced and released to the atmosphere by volcanic explosive events. Each tephra layer has distinctive geochemical marks that can be used as an isochronous marker horizon and mapped mainly on the regional level. However, mainly in the case of tropical events or other major event, if dust is spread for large regions or even globally, in the case of volcanic element markers, then correlation is possible across inter-continental scale distances. These layers provide material for radiometric dating and form a dating framework against which other dating techniques can be checked and validated. Furthermore, these dates establish the ages of the rocks in which the layers are interbeded. Thorarinsson (1944) was the first one to use tephra layers as a chronological tool.

c) Centennial to decadal scale, is the shorter scale of cyclic variations, and can only be identified in very high-resolution records, that is, records found in regions with ultrahigh-sedimentation rates. Most of the known records that show this type of variability cover the Holocene (last 11.5 ky) and the historical period. However, they can be found at any time in the geological scale as far as the archive has the necessary resolution. The best Holocene and historical records are from varve-sediments, speleothems, corals, peat, ring-trees, shells and inner shelf sediment sequences. A very useful dating method for ultrahigh resolution archives is annual layer counting. In all these archives each season is generally identifiable as a distinct layer. In ice deposits, each year is marked by a hard surface or even a melt-layer at the top of the winter ice (Jouzel *et al*., 1987). In lakes, one year is represented by two layers of sediment that differ both in color and thickness, and represent deposits of two different seasons, etc. This is very useful, since layers can be counted from the top, or above a certain depth. However, layer counting cannot be used for dating in itself, it always needs to be combined with more sophisticated methods, such as stable isotopic composition, radioisotope dating, and more recently ice-sheet accumulation modeling, for the case of ice cores.

Radioisotope dating of recent geological materials is based on the short half-lives of the U–Th radioisotopes series. This radioisotope series decay involves a whole series of elements with specific chemical properties. In natural materials that form a closed-system, all the intermediate elements of the series decay are present in equilibrium amounts. If one of those closed-systems breaks down and dissolves, each element can behave differently and equilibrium will be destroyed. Yet, it is exactly this different behavior between diverse atoms that allows their use to measure time. The dating of corals and speleothems, for example, is based in the decrease of ^{234}U, which is expected to be in equilibrium with an isotope of thorium within these calcium carbonate formations. However, as ^{230}Th results from the decay of ^{234}U, a build up of ^{230}Th occurs with carbonate aging, providing a precise dating method designated by Uranium-Thorium dating. This method is useful for dates between 1000 and 300 000 years (Levi, 1990).

Excess thorium-230 (^{230}Th) is another method based on disequilibrium. ^{230}Th isotope, with a half-life of 75.38 years is insoluble; as such its concentration in seawater is mainly the result of their parent isotopes decay (Ritchie *et al*., 1973). However, ^{230}Th is preferentially deposited in the sediments, that is, in abundances that exceed the amount that should be present if in equilibrium with its parent isotopes. Through time, the excess decays away. This allows the determination of age at any one level in a sedimentary sequence, from the ratio between $^{230}Th/^{232}Th$ in the seawater-derived component of the sediment.

Another isotope that has been used for the most recent marine and lake sediments is Caesium-137 (^{137}Cs) (Ritchie *et al*., 1973). ^{137}Cs is a radioactive isotope formed by nuclear fission of ^{235}U and other fissionable products in nuclear reactors and weapons, that is, in the environment it is an anthropogenic atom. It has a short/medium lifetime (30.17 years) and spreads easily in nature given that its most common chemical compounds are highly soluble salts. Dating with ^{137}Cs is possible for sediments deposited after the 1945 Trinity test (the first atomic bomb explosion), by observing the characteristic gamma rays emitted by this isotope. The method is applicable all around the globe, but better results are obtained in the areas enclosing an accident site for which the time of release into the environment is well known.

Luminescense is a methods not much used in dating for reconstructions, however, it is a technique that could be useful, since it is applicable to a wide range of sediments and might help dating fluvial, eolian and fired material deposits in marine or lacustrine environments for example. Luminescence (L) is the amount of energy absorbed from the sun or intense heat and stored in the imperfect lattices of quartz, feldspar or calcite crystals at a known rate, when these minerals were exposed to one of those sources of energy. There are two main types luminescence techniques used for dating; the Thermal Luminescence (TL) and the Optically Stimulated Luminescence (OSL). TL is mainly used for dating of materials that were heated by fire, while the OSL is mainly used to determine age in sun-exposed grains. Both techniques are based on the emission of the stored energy, and the obtained age is the time since the last exposure to sunlight or intense heat. L dating is good between a few hundred to a several hundred thousand years, and the advances in the technique already allow the dating of individual grains (Jacobs *et al*., 2007).

– The problem of reliable chronological framework for time-slice Reconstructions

Another way of doing reconstructions is through what is designated by time-slices in opposition to the time-series presented in the introductory text. These studies, attempt a spatial reconstruction of proxies for variables of the climate system. The first known attempt of such type was the well-known CLIMAP study, that reconstructed the last glacial maximum (LGM) temperature from the definition of an empirically defined function between modern ocean sediment cover planktonic foraminiferal assemblages and sea surface temperature (SST) (Imbrie & Kip, 1971).

The need to understand how the main patterns and modes of climate variability look like and operate from orbital to sub-decadal timescales; to which extent climate variability and climate extremes relate to primary forcing factors and what are the feedbacks that operate to modulate the climate response are key questions that are still unsolved. PAGES 2K working group has selected those key questions as main objectives to be investigated the spatial conditions at 2,000 years. The group within this initiative is compiling data at the regional level and processing the best time series of variables of the climate system. The produced maps are then compared with the best ensemble runs of existing ESMs (http://www.pages-igbp.org/workinggroups/2k-network). The major challenge in this exercise is to standardize the chronology or age models for each set of sites that pass the quality screen.

Another ongoing time-slice type program, that is attempting to respond the question of how past abrupt and extreme climate change relate to primary forcing factors over the period between 60 000 to 8 000 years ago is INTIMATE. In this case, rather than a regional approach, the objective to combine paleoclimate records from ice, marine, and terrestrial environments and use the combined data spatial trend in climate models. Again, scrutinize the quality and develop and improve a coherent dating framework that allows the comparison of records on a common and reliable chronological framework is the main concern. Furthermore, the program hopes to get insight on ecosystem responses to those abrupt and extreme climate variations in space and through time.

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