The scale-dependence of strata-time relations: implications for stratigraphic classification

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ABSTRACT: The establishment of chronostratigraphic units such as geological Systems and Series depends upon an ability to equate succession in rock strata with the passage of time, and upon a pervasive Law of Superposition. These assumptions hold true at a gross scale. But, at fine scales of stratigraphic resolution, they commonly break down. Thus, bioturbation in Phanerozoic marine deposits typically homogenizes sedimentary packages spanning millennia, affecting biostratigraphic, isotopic and paleomagnetic signals, and post-burial mass transport phenomena such as large-scale sedimentary slumps and intra-stratal diapirs locally disrupt superpositional relationships on a larger scale. Furthermore: the multi-stage transport of microfossils prior to final burial complicates the relationship between depositional and biostratigraphic ages; paleomagnetic signals, imposed at shallow burial depths, may be distinct from depositional ages; and high precision zircon U-Pb dates from tuff layers determine time of crystallization in the magma, rather than depositional age. In such circumstances, depositional units cannot be unambiguously equated with time units: because they include multiple temporal components, they cannot be subdivided precisely into time-rock units. By contrast, the different phenomena which have contributed to constructing sedimentary deposits, pre-, syn- and post-depositional, may be effectively accommodated within a unitary geological time framework.

INTRODUCTION

In a previous paper (Zalasiewicz et al. 2004a), members of the Stratigraphy Commission of the Geological Society of London examined the long-standing dual classification of geological time into units of geological time (of geochronology sensu stricto: geological Periods, Epochs and so on) and units of time-rock (of chronostratigraphy sensu stricto: geological Systems, Series, consisting of all the strata deposited within the equivalent geological time unit). We (a large majority of, though not the entire, Commission membership) proposed that they may, with the widespread application of the GSSP (Global Stratotype Section and Point: = 'golden spike') principle, be unified.

The proposal proved controversial, with marked polarity between supporters (Gong et al. 2004; Odin et al. 2004; Jensen 2004) and opponents (Heckert and Lucas 2004; Bassett et al. 2004; Narkiewicz 2004). Where the continued use of time-rock classification in stratified successions was championed, this was on the grounds of (a) logical and philosophical necessity, as a separation of evidence and inference; and (b) utility, as a formal means of dividing strata into packages based upon their time of deposition.

While the second point is one of perspective, and needs discussion among different communities within – and beyond – the earth sciences, the first point represents a more formal objection. We have argued (Zalasiewicz et al. 2004a, b) that the logical necessity of the dual classification is a truism, as all our evidence comes from the rock record. Here we further consider this question by taking another perspective, that of the scale of stratigraphic resolution. We question the correctness of time-rock classification in subdividing strata at the detailed levels now commonly being attained, and examine the relationship between time and the nature of the stratified record.

WHERE SUPERPOSITION BREAKS DOWN

The law of superposition is fundamental to the equation of time and rock strata, and to the subdivision of rock strata into units defined by the time of their deposition. Time-lines are commonly drawn through sedimentary successions to illustrate this process. Various methods may be used to provide proxies for time, though the use of fossils to date Phanerozoic strata remains by far the most widely applied; there is a general assumption that the death and burial of fossils is contemporaneous with the deposition of the enclosing sediments.

At the gross scale, this has provided an effective means of classifying the world's rock strata. The process has been so widely adopted that it has been considered by many geologists that the classification of rock strata by time (i.e. into chronostratigraphic or 'time-rock' units such as Systems and Series) is a necessary precursor and accompaniment to the setting up of the parallel scale of 'abstract' time (i.e. the establishment of Periods, Epochs and so on).

However, the last few decades have seen the attainment of ever-greater levels of stratigraphic resolution. For instance, the Quaternary Period (*sensu* Gibbard et al. 2005) of some 2.6 million years duration is divided into 104 marine isotope stages which approximately reflect Milankovitch periodicities, and are of some few to several tens of thousands of years in duration. The penultimate three of these (relating to the last glacial stage, i.e. oxygen isotope stages 5d-2) include 26 millenial-scale Dansgaard-Oeschger units (Dansgaard et al. 1993), defined on the basis of sub-Milankovitch scale oxygen isotope and climate oscillations. In the current interglacial phase (the Holocene Period), lake, ice-core and speleothem records commonly yield decadal to annual stratigraphic resolutions (e.g. Cuffey 2004). At a local scale, yet finer-scale stratigraphies can be resolved within, for example, volcanic deposits (e.g. Brown and Branney 2004).

The drive towards this increased stratigraphic definition has not come simply from a desire for an increasingly refined and ordered Earth history *per se*. It has been generated by the need - currently compelling - to understand what controls environmental change (and environmental stasis). The finer the stratigraphic resolution, the better the chance of being able to determine whether, say, sub-Milankovitch climate fluctations are synchronous across northern and southern hemispheres (Lynch-Steiglitz 2004), or whether temperatures are synchronous with, lead or lag changes in greenhouse gas levels: the better the chance, therefore, to be able to place effective constraints on models of how the earth system functions. It is within this context that we consider strata-time relations.

VIOLATIONS OF SUPERPOSITION

At fine levels of stratigraphic resolution, we can identify major violations of superposition and of the equivalence of time and rock strata. These are:

Bioturbation and pedoturbation

The sea floor today is almost ubiquitously aerobic, with few exceptions (e.g. the Black Sea, the Santa Barbara and Carioco basins, studied as analogues for early Paleozoic and older ocean floors that were frequently anoxic). Thus, bioturbation, the churning of just-deposited sediments by benthic organisms, is also near-ubiquitous. The surface layer is thus a mixed unit of sediments laid down over a time interval which reflects the ratio of the rate of deposition to the rate and depth of burrowing. The mixing of particles may not simply equate to homogenisation, but may reflect size-controlled sorting in the mixing layer, with larger particles (such as foraminifera) being preferentially transported upwards during the burrowing process (Brown et al. 2001).

Even though oceanographers seek locations where the ratio of sedimentation to mixing is high, the blurring of the record is a significant, and locally impassable, barrier to ever-greater stratigraphic resolution (Schiffelbein 1984). Over most of the deep sea floor, sedimentation rates are 1-5 cm/kyr and here Milankovitch-scale stratigraphic signals are preserved, while millennial-scale signals are generally not (Anderson 2001). Millenial-scale stratigraphy only becomes discerned, albeit generally in attenuated form, where sedimentation rates significantly exceed 5 cm/kyr (e.g. Charles et al. 1996; see also Wheatcroft 1990). Comparable constraints will hold for many ancient 'pelagic' deposits laid down on oxygenated sea floors, such as the bulk of the Cretaceous Chalk deposits, and compromise estimates of stratigraphic completeness (Anders et al. 1987). Like the marine record, terrestrial environments are also subject to vertical mixing, such as the biologically-stimulated turnover in modern soils and their equivalent paleosols (e.g. Stevens et al. 2006).

Not all such synsedimentary churning is biological. Physical process-stimulated turnover occurs in environments with ephemeral saline crusts and in cycles of freeze-thaw action, while high-latitude shallow shelf sediments during glacial intervals are extensively scoured by iceberg keels (Bibeau et al. 2005), the effects being comparable to those of bioturbation, but of considerably greater scale.

The law of superposition thus holds between individual strata but not necessarily within them. At the hand specimen scale, the particles deposited over thousands of years are inextricably mixed, and stratigraphically 'up' and stratigraphically 'down' cannot sensibly apply. Nor, if a geological time boundary (say the Neogene/Quaternary boundary) goes through such a layer, can one part of the rock be separated as part of the Neogene System and another as part of the Quaternary System. One may, though, be able to distinguish microfossils of Neogene and Quaternary age in a sample from this interval, and recognise their relative stratigraphic displacement.

Consider a unit such as the Younger Dryas, a millennial interval of intense cold separating the Allerød warm interval at the end of the last glacial maximum from the early Holocene warm phase. This interval offers some of the clearest insights into mechanisms of rapid climate and sea level change, and precise correlation of this interval may be made in, say, ice core and varved lake deposits (Brauer et al. 1999). However, over large parts of the present ocean floor where sedimentation is slow, this interval cannot be said to be represented by a specific stratum, for bioturbation has mixed thoroughly sediments of this depositional age with the adjacent older and younger deposits

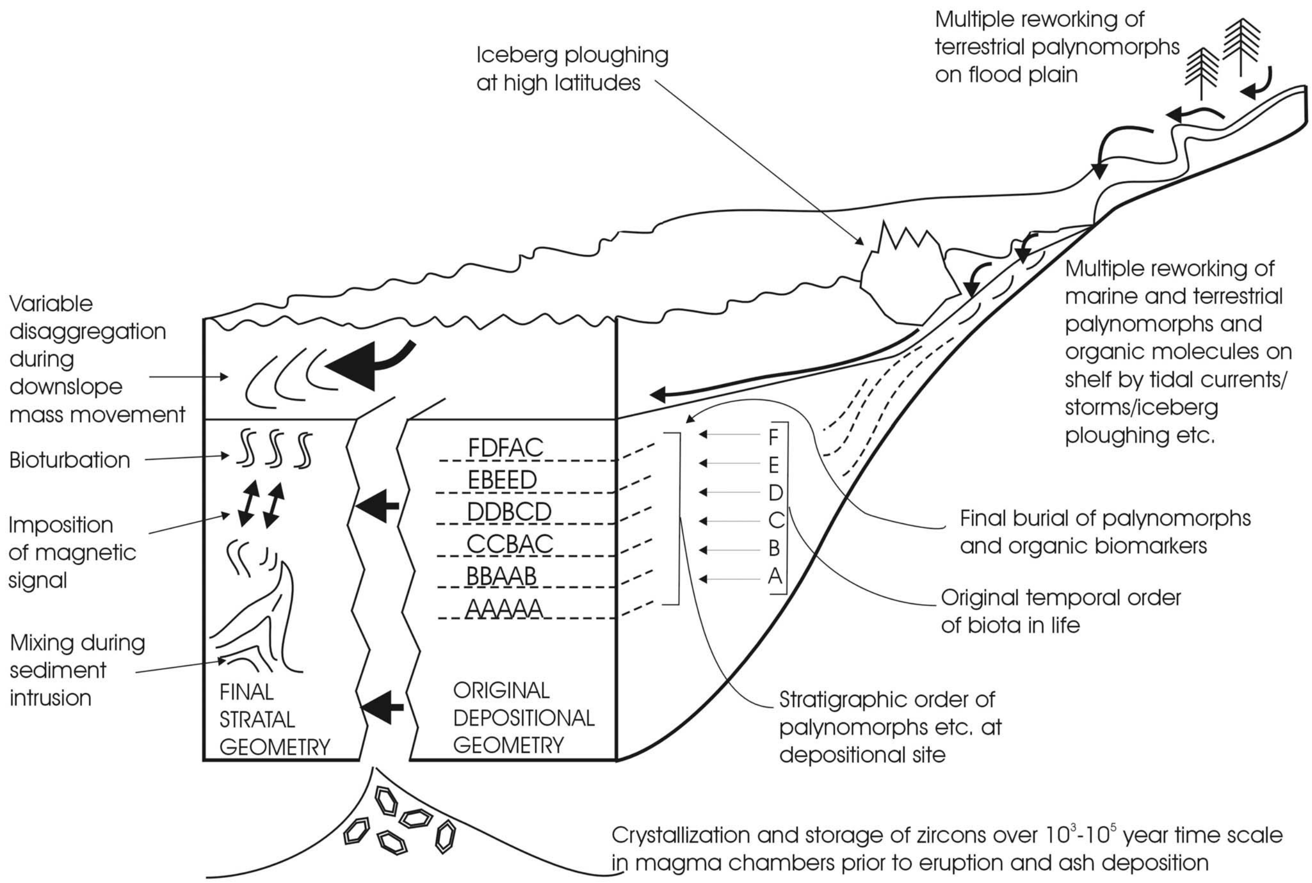

FIGURE 1
Cartoon showing some of the more important mechanisms by which temporal signals are decoupled from the superpositional succession.

(Anderson 2001). At such places, a Younger Dryas Chronozone (i.e. a discrete unit of Younger Dryas depositional age) cannot be said to exist, although events that took place in Younger Dryas time might still be inferred from the deposits.

Post-burial physical changes

These include localized, commonly large-scale phenomena that also violate the law of superposition. Examples include:

Slide/slump deposits: Side-scan radar studies have illuminated the considerable extent of catastrophic slumping on modern continental slopes. Similar deposits presumably formed as frequently in the geological past, and identified examples likely represent underestimates, as the large scale of these phenomena may preclude their identification in natural exposures. High-resolution seismic studies (e.g. Lee and Chough 2001) have elucidated their origins and patterns of internal structure. Commonly, around the top of the scar, there are barely-moved slabs of strata, which we can say represent time interval A. Downslope, these gradually disintegrate into smaller, more disrupted slabs, which in turn may give way into an olistostrome and finally, into a megaturbidite of depositional age B. At no precise point can such a variably transported and reworked stratal mass be said to change from 'being' of one time into 'being' of another. With a unitary time framework, there is no inherent problem in identifying temporally distinct events within the deposit, such as original deposition, slump processes and subsequent final settling. Neither the entire complex mass nor any part of it has to 'be' of any individual age.

Diapirs: Underground remobilisation of deposits as diapirs is increasingly recognized. Deposits range from small-scale interstratal sedimentary flow layers (Kawakami and Kawamura 2002), to the mudlumps of the Mississippi delta (Coleman et al. 1998), and the kilometre-scale sandstone intrusions of the Faeroe-Shetland basin (Shoulders and Cartwright 2004); many petroleum reservoir deposits have been thoroughly remobilised and injected into overlying strata (Huuse et al. 2003). Such diapirs contain fossils of the original depositional time interval, albeit variably reshuffled, but have acquired new superpositional relations (which include the surface, when the diapirs break through). The deposits may be said to be a product more of the injection events than of their original deposition. Their assignation to time-rock units is problematic, as is those of nearer-surface disturbance resulting from dissociation of methane hydrates.

TEMPORAL MISMATCH BETWEEN DEPOSITION AND DATING TOOLS

Here we examine related aspects that are not in themselves formal violations of the depositional versus temporal record, in that they do not reshuffle particles from their original depositional positions. Nevertheless, they represent significant practical difficulties in equating the deposit with the time record.

Reworking of fossils

While the reworking of fossils from one deposit to another has long been recognised (as derived fossils), it is generally assumed, for practical purposes, that the death and entombment of organisms was effectively synchronous with the deposition of the sedimentary particles. Exploitation of this assumption has proved exceptionally effective in providing a relative time-scale for Phanerozoic strata. However, the increased use of easily reworkable microfossils such as palynomorphs and calcareous nannofossils, and the increasingly precise stratigraphic resolutions being sought, mean that this assumption of precise age-equivalence of sediment and fossil needs to be questioned.

The extent of reworking of palynomorphs at long temporal scales may be seen in the preservation, in southern Britain, of Paleozoic, Mesozoic and Paleogene palynomorphs of various ages in Pleistocene marine and glacigenic deposits of, for example, Thurnian-Baventian, Cromerian (?MIS 16) and Devensian (MIS 2) age (Riding et al. 1997; Lee et al. 2002; Riding et al. 2003, respectively), the presence of Cretaceous palynomorphs in present-day glacial deposits in Antarctica (Riding, pers. com. 2006) and of Devonian to Permian miospores in early Triassic strata of northern circumpolar areas (Utting et al. 2004). Such reworking may be recognized by biostratigraphic mismatches and preservation/thermal maturity differences.

At shorter time-scales, reworking is harder to recognise, as exemplified by the problem of discriminating microfossil reworking from survivorship around the K-T boundary (Minoletti et al. 2005; Bown 1995). Reworking at yet shorter time-scales is inherently cryptic, but is likely to be widespread. For instance, pollen input into the terrestrial and shallow marine deposits of a sedimentary basin is via wind or water. With fluvial transport, a significant proportion of the pollen load is commonly temporarily stored in catchment soils, then subsequently (and repeatedly) on floodplains; it is exhumed and re-transported as channel migration proceeds. Similarly, once deposited on a shallow sea floor, repeated episodes of burial and re-exhumation by storm action (or, locally, by iceberg ploughing: see above) may take place: this process correlates inversely with completeness of a shelf sedimentary succession *sensu* Sadler (1981) and Sadler and Strauss (1990), prior to final burial. Robust microfossils of both terrestrial and marine origin may be reworked in this way, hence a significant proportion of the microfossils in a deposit may be subfossil and may seriously affect precise correlations.

Bulk burial of pre-aged organic matter

The equivalence in age of fossils and associated environmental indicators within a deposit has been a key assumption underlying studies of late Quaternary climate. However, this assumption has been shown to be markedly invalid for some marine successions, with haptophyte-derived alkenones in Bermuda Rise sediments showing a temporal offset (i.e. being older than) co-existing foraminifera by up to 7000 years (Ohkouchi et al. 2002) because of long-term lateral transport along sediment drifts (organic-walled microfossils, of course, may show a similar pattern). This observation led McCave (2002) to observe, strikingly, that the Holy Grail of contemporary marine stratigraphy - rapidly deposited successions providing high-resolution paleoenvironmental records – may rather be a poisoned chalice, with multiple temporal components blurring their fidelity even where bioturbation has not been significant.

Post-depositional diagenetic imprints

Important processes affecting sediments after deposition include the production of diagenetic mineral phases (Curtis 1985). Indeed the orbital signal recorded in sediments is sometimes a product entirely of diagenetic processes. Gale et al. (2005) recorded the obliquity and eccentricity signal in Eocene-Oligocene paleosols from illite abundance, a product of diagenetic illitization of smectitic soils through wetting and drying of soils. Likewise, beds of flints in Cretaceous chalks are entirely a diagenetic product, but accurately record a Milankovitch signal (Wray and Gale 2006). In such cases, the time difference between deposition and diagenesis is a maximum of about 10^2 to 10^4 years, reflecting respectively the durations of precession and obliquity.

Delayed imprint of paleomagnetic signals

Changes in magnetic field polarity, recorded in sediments (i.e. magnetostratigraphy), are modulated by a variety of physical and chemical processes (Carter-Stiglitz et al. 2006). The lock-in depth of the magnetisation (due to the magnetic field) may correspond to both very short intervals (Katari et al. 2000), or be acquired over a longer time, in part controlled by various sediment fabric modification processes, such as bioturbation and initial compaction. These complex magnetisation lock-in processes may cause the apparent absence of short duration excursions in the magnetic field record of sediments (Roberts & Winklhofer 2004). Similarly, in the case of some Chinese loess successions, the mismatch between the base of the recorded Brunhes magnetozone, and the depositional age is equivalent to a sediment thickness of some 22 kyr, in comparison to the climatic record preserved within the soil-loess successions (Spassov et al. 2003).

U-Pb geochronology of volcanic ash zircons: crystallization and residence time

Improvements in U-Pb geochronology, aimed at dating crystallization time of zircons contained in volcanic ash deposits, have considerably improved understanding of the time sub-division of the Phanerozoic. However, analytical data is now such that secondary precision-related (open-system) behaviour in U-Pb systematics (Schoene and Bowring 2006), crystallization duration and zircon residence time in the magma chamber have become important. Where crystallization durations have been estimated, they suggest growth in <200 kyr (Schmitz and Bowring 2001). Residence times of the magma chambers producing the zircons is difficult to constrain, but likely varies between 1 and 600 kyr (Schmitz and Bowring 2001). These indicate that irrespective of the accuracy of the U-Pb zircon geochronology, times of crystallization will always predate the depositional age of sedimented ash, by amounts of time that are difficult to define, even in the best of circumstances.

DISCUSSION

We have shown that, at fine (~millenial) time scales, those physical constituents of strata (sedimentary particles, fossils, chemical patterns and so on) that relate to the timing of deposition are commonly not arranged in a superpositional pattern. Rather, they have been mixed by a variety of processes taking place both before sedimentation (e.g. cryptic transport/reworking of microfossils) and after burial (e.g. mixing through bioturbation). At these scales, therefore, the physical discrimination of sedimentary successions into depositional units reflecting distinct time intervals – i.e. into chronostratigraphic units – is not consistently achievable. The relationship between sedimentary rock and time is inherently complex, and there are finite (and uncertain) limits to the extent to which time and depositional process can be disentangled from the preserved stratal record.

This being so, we infer that the maintenance of a chronostratigraphic *sensu stricto* scale of time-rock units, separate from but temporally and hierarchically equivalent to a scale of geological time (geochronology *sensu stricto*), is not an inherent or logical necessity.

The geological time scale of Periods, Epochs and so on is indeed derived (for the Phanerozoic + Ediacaran) from the physical stratal record. The evidence on which the time scale rests includes the strata themselves, classified using lithostratigraphy. The evidence also includes fossils (biostratigraphy) and an increasing array of isotopic, chemical, magnetic and other patterns. Each of these have their own form of stratigraphic classification. In many of these, the notion of stratigraphically 'up' or 'down' represents a valid topological distinction, independent of temporal significance; it is a fundamental descriptive component in particular in lithostratigraphy. However, as this character does not simply and unambiguously reflect the precise timing of deposition, we conclude that it cannot be fundamental to the subdivision of geological time. Thus, there is no logical *necessity* to formally classify strata with regard to the timing of their deposition, given the scale-dependent limits to such classification.

There is a separate question relating to the *usefulness* of time-rock classification. This remains as an optional means of classifying strata - but not unstratified rock bodies such as metamorphic complexes (Zalasiewicz et al. 2004a, b) - at broader levels of correlation, a form of shorthand which is familiar, convenient and useful to some earth scientists but not to others. For, in the earth sciences, the temporal/topological association of upwards = younger (and vice versa) remains deeply rooted. Outside the earth sciences, this association is less familiar.

On balance, we consider that geological enquiry would be best served by the consideration of stratigraphic process with respect to a unitary scale of geological time. This stance would emphasize rock strata as complex, multi-component archives of geological process, in which the temporal information may commonly be variably disorganised with respect to the vertical succession. Recognition of this reality, and of the problems stemming from it, is vital in deciphering the precise course of the Earth's environmental and climatic history.

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