Terrestrial stratigraphical division in the Quaternary and its correlation

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Abstract: Initially, terrestrial evidence formed the foundation for the division of Quaternary time. However, since the 1970s there has been an abandonment of the terrestrial stage chronostratigraphy, which is based on locally dominated successions, in favour of the marine oxygen isotope stratigraphy which largely records global-scale changes in ice volume. However, it is now clear that glacial records around the world are asynchronous, even at the scale of the continental ice sheets which display marked contrasts in extent and timing in different glacial cycles. Consequently, the marine isotope record does not reflect global patterns of glaciation, or other terrestrial processes, on land. This has led to inappropriate correlation of terrestrial records with the marine isotope record. The low resolution of the latter has led to a preferential shift towards high-resolution ice-core records for global correlation. However, even in the short term, most terrestrial records display spatial variation in response to global climate fluctuations, and changes recorded on land are often diachronous, asynchronous or both, leading to difficulties in global correlation. Thus, whilst the marine and the ice-core records are very useful in providing global frameworks through time, it must be recognized that there exist significant problems and challenges for terrestrial correlation.

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From its earliest beginnings, the study of geology has been fundamentally linked to the study of sedimentary strata and their relationship to each other. This concept provides the very fabric of the subject and its application in presenting and determining the evolution of the Earth through time. This holds as true for the Quaternary as it does for any other part of the geological column. Therefore the division of the successions that record the passage of events and time provides the central pillar of palaeoenvironmental and landscape reconstruction through the period.

Since the 19th century, when it was recognized that glaciers had been far more extensive than today, the basis of Quaternary history had been the distribution and spread of glacial materials in the landscape (specifically tills, erratic rocks and associated meltwater deposits). By late in the century the recognition that glacial ice had extended multiple times, their deposits being separated by fossil-bearing beds yielding evidence that temperate climate episodes intervened, led James Geikie (1894, 1895), among others, to coin the terms ‘glacial’ and ‘interglacial’ to classify these events.

Subsequent development of the divisions and definition of Quaternary time and events naturally followed. One of the most striking themes that recurs through the decades has been the desire to equate events identified from local sequences with ‘global’ records. This has happened against the background of repeated paradigm shifts, starting with the Alpine successions of Penck and Brückner (1911), then the sea-level chronology of Zeuner (1959) and Evans (1971) and most recently the marine oxygen isotope and polar ice-core stratigraphies. Each of these paradigm shifts was seen as a ‘revolutionary’ advance in understanding of what is undoubtedly an extremely complex sequence of climatically driven changes at a range of scales.

Until recognition of the implications of the marine isotope succession in the late 1960s and early 1970s (Shackleton 1967; Broecker and van Donk 1970; Shackleton and Opdyke 1973; Hays et al. 1976) terrestrial evidence formed the foundation for the division of Quaternary time. Today the contrast could not be greater, with many abandoning the terrestrial chronostratigraphical classification in favour of the ocean-floor isotope and ice-core stratigraphies. The driver of cyclic fluctuations in marine oxygen isotopes has long been attributed to orbital forcing (Hays et al. 1976; Imbrie and Imbrie 1980) and this has underpinned the timeframe to which both the marine isotope and ice-core records are tuned (Imbrie et al. 1984; Dansgaard et al. 1985; Ruddiman et al. 1989; Bender et al. 1994; Lisiecki and Raymo 2005). Whilst undoubtedly the marine isotope and ice-core sequences offer a reliable framework, it is essential to remember that these sequences, especially those in ocean-bottom sediments, record both regional and global-scale changes. This contrasts substantially with terrestrial or shallow marine sequences which preserve locally dominated successions, reflecting local and regional events. Such events are not necessarily represented in the global patterns because the local responses to changes will inevitably lead to modifications to any all-encompassing pattern. For this reason direct correlation of terrestrial sediment sequences with those in the oceans and those in the ice cores should not be undertaken uncritically. Lessons from the past have repeatedly shown that simplistic or mechanistic correlation, when examined in detail, is often inappropriate and unsustainable.

The complexity of events shown by high-resolution palaeoenvironmental investigations, such as those from the ice cores, have allowed the recognition of ever more climatic oscillations of decreasing scale. Consequently ‘event stratigraphy’ is now applied to the subdivision of ice-core records and is widely applied and indeed advocated for wider terrestrial correlations in some contexts (e.g. Hughes and Gibbard 2015; Lowe et al. 2019; see below). The recognition of these events has substantial implications for our understanding of the nature of landscape development and terrestrial evolution. However, the unravelling of this evolution requires a rigorous time-division foundation. The reconstruction of
events should use all available lines of evidence to ensure a rigorous local and regional chronostratigraphical scale. Over reliance on ice-core event stratigraphy, such as Greenland interstadials or stadials, for global correlation could lead to the same erroneous correlations that have arisen from attempted equation with marine isotope stages (Hughes and Gibbard 2015). This point is reinforced by the fact that events resulting from the same causative agent are not necessarily globally or even regionally isochronous (see below).

This review examines the bases for construction of terrestrial sequences and their subdivision and, in turn, assesses the validity of their correlation with extra-regional and ‘global’ stratigraphies. Finally, important recent and potential future developments are also considered.

Terrestrial geological successions

It is natural that the first observations of sedimentary sequences and landforms should begin with our observation of the landscape we inhabit. Therefore in the early development of geology, it was to be expected that investigations primarily focused on the spread of glacial sediments, with the realization that glaciers had in the recent past been more extensive than today (see the review in Hansen 1970). These studies necessarily began in mountain regions, especially the Alps where glaciers were already present, but later extended to the plains of Europe and beyond when it was realized the ice had once extended from an ice centre in Scandinavia, as well as smaller centres such as those in Britain including the Scottish and Welsh mountains and the Lake District. At much the same time there was a realization that shallow marine and coastal sediments in the North Sea and Paris basins and the raised shorelines of the Baltic and Mediterranean regions indicated that sea-level had equally changed very recently in geological terms.

From these early observations the development of Quaternary geology, and the realization that climates of the recent past have changed profoundly, has been principally based on the study of terrestrial or shallow marine sediment sequences and landforms. It is this evidence that until relatively recently provided the sole source of our records and sequence of events through the critical time interval.

Sedimentary environments reflect the interaction of physical, chemical and biological conditions under which the material accumulates (Krumbein and Sloss 1963). The interplay determines the properties of the sediments deposited in an environment and in turn determines the pattern and distribution of the sediments deposited. For stratigraphers, it is essential to understand the nature of such environments, their persistence or otherwise through time and their geographical distribution if they are to reconstruct accurately the sequence of sediments and landforms and their evolution. The climatic and environmental significance of the contained fossil assemblages further enhance and in many cases determine the interpretation of these parameters. Moreover they provide the basis for constructing time equivalence or correlation in distant sediment sequences.

For the stratigrapher to reconstruct past environments accurately, a knowledge of sedimentary processes, based on modern-day observations, is essential. These observations must not only be based on physical, chemical and biological process themselves, but also the nature of the sediments formed in a specific situation and the processes involved in preservation of forms and fossil assemblages alike. Only in this way can the products be interpreted in a meaningful and accurate manner.

The occurrence of a terrestrial sediment sequence in any place implies that the material was derived from a source area, where presumably the debris was produced as a product of breakdown or pre-existing rock or sediment. The debris is then transported by some means, during which it may or may not be modified, and finally it is deposited. Minor exceptions will be chemically precipitated deposits, biogenic deposits or volcanic dust products. Subsequent activity may result in modification of the deposited material by physical chemical processes, such as weathering, or soil formation, and by plants or animals.

Whilst whole books have been written addressing the concepts of sediment-process modelling, facies and architectural analysis and taphonomic process investigations, it is not the purpose of this review to address a classification of sedimentary environments. Instead it is to consider the stratigraphical approaches to terrestrial and shallow marine stratigraphical sequences, both their correlation and age determination.

Terrestrial environments and materials

Terrestrial evidence is defined here as of rocks, sediments and landforms found on or near land. Put in the simplest of terms, the nature of the terrestrial or continental environment is one of erosion where, in general, natural processes break down pre-existing rocks and sediments (cf. Longwell and Flint 1962). These areas are by their nature those above sea-level. However, the rapidity and scale of changing sea-level in the Quaternary means that continental environments also occur in fossil form below sea-level to depths in excess of 100 m in coastal regions. Equally, in areas of isostatic uplift shallow marine sediments may occur elevated to over 200 m in regions subject to this process. For this reason, coastal and shallow marine sedimentary sequences and landforms can be included within the general heading since they are effectively transitional in nature (cf. Krumbein and Sloss 1963).

On land sediment deposition occurs in a vast range of environmental situations including rivers, lakes, estuaries, coasts, marshlands (paludal environments), peat bogs, valley sides, solution hollows, caves, dune fields, volcanoes, and in front of glaciers, etc. The sediments may be clastic, chemical precipitates or biological materials. The variety of sediments produced in these situations is as diverse as the environments themselves. An important characteristic of terrestrial sediments is that at the surface they are expressed as landforms and thus terrestrial sediment sequences are not only recorded in vertical section as geology but also recorded by landforms at the Earth’s surface. This characteristic means that terrestrial sequences can also be subdivided and correlated based on their morphology, i.e. morphostratigraphy, which is defined as the subdivision of sedimentary or rock units primarily from the surface form that they display (Frye and Willman 1962). Morphostratigraphy is widely employed in Quaternary science to subdivide a range of sedimentary successions and is a key component of geomorphology – the study of Earth surface processes and landforms (Hughes 2010, 2013). Since morphostratigraphy is inherently very fragmentary, correlation can be made with nearby quasi-continuous records which can act as a parasequence in order to build a chronostratigraphical record, which ideally provides a record of continuous time. For example, moraine records in Greece (Hughes et al. 2006) were correlated with the pollen stratigraphical record from Lake Ioannina (Tzedakis 1994; Tzedakis et al. 2002) in order to formally define a cold stage chronostratigraphy for Greece (Hughes et al. 2005).

The nature of terrestrial sedimentation is governed by its geographical limitations in terms of the distribution, occurrence and by the climatic determinants. Climatic changes in the Quaternary further limit the occurrence of specific sedimentary sequences since the controlling processes are inevitably determined very strongly by the prevailing climatic conditions operating at any one place at any one time. The effects of these conditions on ongoing surface processes mean that morphology alone is often insufficient for correlating Quaternary terrestrial sequences, and the most complete and continuous records tend to occur in polar ice.
Quaternary (Morrison and Wright 1965). Where the main property of the latter is the ultimate objective for scientists interested in regional and correlation. Both are important for Quaternary studies, although based on their properties or attributes (Salvador 1994, p. 137).

Stratigraphical frameworks and the organization of terrestrial environments are the focus of the investigations for whatever purpose. A detailed study of this type should not be considered of any less importance in the case where the sequence cannot be considered temporary since the sediment stored on the land at any one given time is in transit to the sea, its ‘final resting place’. The sediment therefore has a low preservation potential on a geological timescale. Nevertheless, since it is deposited and we can observe it, there is no reason to consider its stored information to be less useful than that from marine sediments. The study of terrestrial sequences is clearly of central importance for study where local or specific environments are the focus of the investigations for whatever purpose. A detailed study of this type should not be considered of any less importance in the case where the sequence cannot be correlated to a global scale.

The correlation of terrestrial sediment sequences relies on robust stratigraphical frameworks and the organization of terrestrial sediments and landforms into distinctive, useful, mappable units based on their properties or attributes (Salvador 1994, p. 137). Stratigraphy comprises two basic elements, sequence subdivision and correlation. Both are important for Quaternary studies, although the latter is the ultimate objective for scientists interested in regional palaeogeographical reconstructions, which in turn can be correlated with the major global climatic events that characterize the Quaternary (Morrison and Wright 1965). Where the main property or attribute includes landform morphology, sediment characteristics and sediment architecture, their organization into distinctive, useful, mappable units can be achieved following three approaches: morphostratigraphy, lithostratigraphy and allostratigraphy (Hughes 2010). In the vertical section, terrestrial stratigraphical correlation is also commonly facilitated by biostratigraphy (Tzedakis et al. 2001) and advances in sediment core-scanning have led to an increase in stratigraphical subdivision using techniques allied to lithostratigraphy, such as geochemistry and tephrochronology. The basis of these approaches and their use in Quaternary stratigraphy is outlined briefly below.

Stratigraphical implications

Whilst tectonics and climate are the principal drivers of terrestrial landscape evolution, their impact is in all cases modified by local factors. The products of terrestrial mass-wasting and transport are overwhelmingly of local character and distribution. This great range of processes operating, the rapidity of climatic changes and the geographical settings in which terrestrial sediments accumulate combine to make sedimentary sequences difficult to relate to those preserved in external areas. Secondary modification also contributes to this problem. Within various depositional systems, facies variation remains a significant problem when attempts are made to demonstrate equivalence either directly or through geochronology. Sedimentation on land therefore represents the products of highly discontinuous processes, often operating at highly variable rates.

It is often stated that the geological record preserved in sediments is highly incomplete. According to Ager (1993, p.53), ‘the sediment pile at any one place on the Earth’s surface is nothing more than a tiny and fragmentary record of vast periods of Earth history – the “Phenomenon of the Gap Being More Important than the Record”’. If this statement is correct for the shallow marine environments for which it was primarily intended, it is even more so for continental settings where the conditions cause the stratigraphical record to be effectively ‘a lot of holes tied together with sediment’. Given that erosion is the dominant process operating on land areas in general, and non-deposition might be regarded as a secondary determinant, the unavoidable consequence is that a ‘complete’ sequence of events – whatever the term ‘complete’ means in this context – can almost never be preserved on the land at a single locality. This is so even though long records, such as those from lakes or ice cores, may provide sequences spanning several glacial–interglacial cycles, but these are exceptional cases. Sadler (1981) has considered this problem and demonstrated that a complete sequence is one in which no gap in the succession exists that is of longer duration than the timespan at which the sequence is studied; i.e. the finer the scale of measurement, the less complete the succession is likely to be. The implication of the episodic nature of sedimentation is that at very short timespans all sequences are incomplete; what is important is whether the succession can be judged complete relative to the timespan or scale resolution at which the record is required (Smith et al. 2014).

Whilst only a fragmentary record of geological time is normally recorded in preserved terrestrial and shallow marine sediments, it is also important to consider the hierarchy of sequences, i.e. the scale of deposition over time at any one place or area. Clearly, the scale of the component sequences and sedimentary hiatuses separating individual units can differ greatly, and indeed by several orders of magnitude (cf. Miall 1997, 2016). Determining the timespan of these individual component units is a major challenge and one that should not be taken lightly. Accurate and precise time estimates of sequences and hiatuses cannot be achieved by taking bracketing ages from stratigraphically or geographically distantly spaced marker beds (Sadler 1981; Miall 1997, 2016). The same problems hold for palaeomagnetic events where lacunae may result in misleading ages. Nevertheless, accurate correlation demands that sequences be dated either relatively or numerically as precisely as possible. However, shallow marine sedimentation on the shelf may be amenable to seismic stratigraphy. In these cases sequence stratigraphic interpretations are possible, where sequence boundaries (erosional surfaces near shore) can be traced to continuously deposited and hence (potentially) precisely dateable sediments.

These concepts hold true throughout the geological column, but for the Quaternary an additional complication arises from the need to reconstruct the numerous, and often rapid, climatic events now known to have occurred during the period. The consequence is that stratigraphical problems are often uppermost in the minds of Quaternary scientists. Unlike geologists working on pre-Quaternary rocks, we are testing stratigraphical principles to their limit and beyond, often by attempting to subdivide impossibly short periods of time across different environments and then to correlate them beyond local areas. This is particularly obvious, for example, where glaciation is identified in one region, yet beyond the maximum extension of the glaciers it can be difficult to identify and establish the chronologically equivalent non-glacial sedimentary
accumulations; the greater the distance, the more problematic the correlation becomes.

Attempts to overcome this difficulty have led to workers adopting an event-based stratigraphy, an approach which, instead of defining boundaries fixed in time, understands the boundaries to be diachronous, reflecting potential leads or lags in responses across the Earth’s surface (e.g. Björck et al. 1998). This approach is essentially the same as that of climatostratigraphy, long applied to the division and correlation of Quaternary sequences (e.g. Pillans and Gibbard 2012). Whilst this is useful for climatic reconstruction, it can cause confusion with the formal division of time, with its fixed boundaries.

**Extra-regional correlations**

The inherently fragmentary nature of terrestrial records means that many Quaternary researchers understandably look to correlate events on land to those recorded in quasi-continuous records in the deep oceans or in the ice cores. Much of the assumptions surrounding such correlation is the role of orbital forcing on patterns of Quaternary climate change. Indeed, the marine isotopic records and associated marine records are tuned to orbital parameters (Fig. 1). Fortuitously, ice-core records have a semi-independent chronology based on counting of annual accumulation, ice-flow modelling, and the use of climate-independent age markers, such volcanic eruptions (e.g. Parrenin et al. 2007). However, as with marine records, the ice-core stratigraphies also rely on orbital tuning and ice-core chronologies have often been tuned using the same orbital models, such as SPECMAP, as the marine isotope records (e.g. Dansgaard et al. 1985; Bender et al. 1994; Bender 2002). This led Parrenin et al. (2007, p. 486) to note that for ice-core records ‘the accuracy in terms of absolute ages is limited by the hypothesis of a constant phasing between the climatic record used for the orbital tuning procedure and the insolation variations’. Thus, marine and ice-core stratigraphies are often built using the same assumptions of global climate forcing and this inevitably introduces some circularity in the entire basis of Quaternary climatostratigraphy, to which all other records, including those on land, are tied. In addition to this fundamental weakness, which undermines the stratigraphical independence of these records for global correlation, there are other problems and challenges for land–sea and land–ice correlations and these are outlined below.

**Land–sea correlation**

The recognition that the ocean isotope stratigraphy provides a quasi-continuous record of changing climate through the late Cenozoic has driven an inevitable trend towards correlating terrestrial sequences directly with the isotope stages established in the deep-sea succession (Fig. 1). This arises from the desire to correlate fragmentary local sequences to a regional or global timescale, where continuity is the focus. The realization that ocean-floor sediments recorded considerably more events than were recognized on land has led to the replacement of locally established terrestrial timescales over the last few decades. Instead, direct correlations of terrestrial sequences to the global isotope scale have become the norm, as advocated, for example, by Kukla (1977). The temptation to do this is understandable, but since there are serious practical limitations to this approach (cf. Schlüchter 1992), any attempt to cross-correlate should be related to fixed points or marker units or horizons the age of which is not disputed. The recent development of reliable geochronological techniques has further encouraged this trend (Gibbard and West 2000, 2014).

One of the biggest issues in relating terrestrial sequences to the marine isotope stratigraphy is the means by which correlation is achieved and equivalence is established. Whilst in some instances it has proved possible to link directly the marine and terrestrial records using either marker events (e.g. volcanic eruptions), lithologies or magnetic reversals, in the majority of cases the linkage has been based on weak criteria. Indeed there is a strong tendency to over-extend correlation from one or possibly more markers by counting backwards or forwards, or adopting assumed equivalents, often based on interpretation of climatic origin or genesis of sedimentary deposits.

A most successful means of extending and achieving greater, independent accuracy in land–sea correlation is the technique of sequence stratigraphy. This approach relies on the fact that sea-level has undergone rapid relative changes multiple times through geological time, and especially during the Quaternary. Relative sea-level changes arise from transfers of water between oceans and continents during expansion and contraction of ice sheets, driven by climate change (Shennan 2007). They also record vertical movements in the Earth’s crust over a wide range of timescales, from seismic uplift and subsidence, through centennial- and millennial-scale movements driven by glacial isostasy. Vertical changes in relative sea level result in major horizontal shifts in coastal environments. The combination of all these factors means that no single location on Earth records all the changes. The most significant advance in studies of Quaternary sea-level change is the recognition that reconstructions require the integration of multiproxy observations with model predictions for a range of palaeoenvironmental variables, not only through observations or predictions of relative sea level, but by oxygen isotope records from ocean sediments used to reconstruct global eustatic sea-level change through the Quaternary.

In common with many aspects of Quaternary science, research into sea-level changes advanced significantly with the development of improved methods for numerically dating sediment, especially 14C. Early debates noted the regionally different patterns of emerged and submerged shorelines and sediments. Glacio-isostasy partially offered an explanation, but the significance of hydro-isostasy, local tectonics and the effects of gravitational attraction on the ocean surface only became accepted with advances in geophysical models.

As already discussed, oxygen isotope variations (δ18O), in foraminifera preserved in deep-ocean sediments are a major resource for developing continuous reconstructions of ice volume and sea level throughout Quaternary time. Benthic oxygen isotopes record a >120 m glacio-eustatic sea-level lowstand during the Last Glacial Maximum (LGM) (Fig. 1; Spratt and Lisiecki 2016). Moreover, a major shift in the frequency and amplitude of glacio-eustatic sea-level lowstands coincided with the initiation of the c. 100 ka climate cyclicity of the ‘early–middle Pleistocene transition’ at c. 900–600 ka (Maslin and Brierley 2015). Prior to this, sea-level changes of c. 70 m or less occurred within glacial cycles.

Sequence stratigraphy is dependent upon the large-scale, three-dimensional arrangement of sedimentary strata, and the factors that influence their large-scale geometry (e.g. reviews by Van Wagoner et al. 1990; Emery and Myers 1996; Miall 1997, 2016; Catuneanu et al. 2011, Catuneanu 2019). The sequence is a stratigraphical concept based upon the three-dimensional arrangement of strata into units bounded both above and below by successional hiatuses that can be identified and traced from discontinuous accumulations to conformable surfaces in a basinward direction from river mouths or coastal situations (Fig. 2). These surfaces are termed sequence boundaries and the strata that comprise the package represent a depositional sequence. The seismic reflectors from stratal surfaces are chronostratigraphical markers, not lithological horizons as earlier thought, and therefore provide invaluable markers for temporal correlation.
Fig. 1. Graphs showing link between the structure of glacial–interglacial cycles indicated in the global benthic marine oxygen isotope LR04 stack of Lisiecki and Raymo (2005) and global sea-levels extracted from a global of seven sea-level records (from Spratt and Lisiecki 2016). The dust flux graph is from the EPICA Dome C ice-core record in Antarctica and is predominately a terrestrial dust signal and an indicator of the state of the global hydrological cycle with increased dust at times of global glacier maxima (Lambert et al. 2012). The bottom graph shows June insolation data at 60°N (Berger and Loutre 1991; Berger 1992). The Roman numerals (I, II, III, IV etc.) over the global benthic δ¹⁸O stack indicate the positions of the respective glacial terminations. During the glacial cycles associated with weaker global glaciations and higher sea levels (MIS 8 and 10 highlighted in the sea-level and dust graphs), the most severe glaciations recorded by global aridity and the greatest dust flux over Antarctica (indicated by red arrows) were not synchronous with the global glacier maxima indicated by the trough in the marine isotopic record (indicated by the red dotted line). Adapted from Hughes, P.D., Gibbard, P.L., Ehlers, J., 2020. The ‘Missing Glaciations’ of the Middle Pleistocene. Quaternary Research 96, 161–183, reproduced with permission of Cambridge University Press.
In almost all cases the geometrical relationships are identified by
global sealevel change, and may be characterized by condensed marine 
positions of which migrated progressively downward as 
progressively more distal locations, forming a geometrical pattern 
which are transgressive) and the component 
uplift of the depositional area, both of which can 
and may include features such as river valleys or glacial troughs 
and may be thin and 
frequently removed by later subaerial 
erosion forming the unconformity. (B) A type 
lowstand systems tract; SMST, shelf- 
margin systems tract. From Van Wagoner 
margin systems tract. From Van Wagoner
stratigraphical record (Posamentier and Weimar 1993; Pedeja et al. 2014; Catuneanu 2019). On the other hand at certain times, such as during periods of glaciation and deglaciation, high-magnitude, high-rate sea-level fluctuations have undoubtedly occurred.

Although originally based on Quaternary sequences (e.g. Frazier 1974), the approach of sequence stratigraphy has been relatively little-used in Quaternary studies. However, it has been applied not only to near-continental margin situations (e.g. Miller and Mountain 1994; Campo, Bruno and Amorosi 2020), but attempts have been made to also apply it to fluvial (e.g. Blum and Törnqvist 2000) and indeed glacial depositional successions, the latter most frequently in situations where glacier tongues or ice shelves terminate in the sea or large lakes (e.g. Boulton 1990; Eyles and Eyles 1992; Brookfield and Martini 1999).

In older geological successions sequence stratigraphy is now widely used as a means of subdividing, correlating and dating sediment accumulations, especially in the hydrocarbons industry (e.g. Posamentier and Vail 1988). It should also be noted that sequence stratigraphy is often applied uncritically; in particular, age assignment of strata based solely on correlation with a supposedly global sea-level curve has not proved to be a robust method. Nevertheless, as Posamentier and Weimar (1993) have suggested, this method holds considerable potential for increasing accurate land–sea correlation during the Quaternary.

**Land–ice correlation**

There has been a trend in the last few decades towards reliance on ice cores for terrestrial correlation. This is especially the case for the Late Pleistocene, since the longest ice cores in the Northern Hemisphere (Greenland) span this interval cycle (Björck et al. 1998; Walker et al., 1999; Lowe et al., 2001, 2008; Blockley et al., 2012). Ice-core records from Antarctica are much longer and span multiple glacial–interglacial cycles over the past 800 ka (EPICA 2006). The advantage of ice cores over ocean records is one of resolution. The ice cores offer an unrivalled annual resolution for reconstructing environmental change and as such offer potential for fine-scale land–ice stratigraphical correlations. However, there are limitations to relying solely on event stratigraphy for global correlation.

Ice cores provide geochemical archives related to a variety of different environmental indicators. Oxygen and deuterium isotope records in ice cores are related to air temperatures over the ice sheet at the time of snow precipitation and subsequent accumulation (Johnsen et al. 2001; Jouzel et al. 2007). Dust particles in ice cores provide a record of atmospheric dust flux over the ice sheets (Lambert et al. 2012). Antarctic dust records are broadly representative of the global hydrological cycle with increasing dust, indicating a cooler and drier global atmosphere that is directly associated with the extent of global glaciations (Hughes et al. 2020).

A comparison of Antarctic ice-core dust records with loess/palaesol sequences from the Chinese Loess Plateau (Kukla et al. 1994) appears to support the synchronicity of global changes in atmospheric dust load (Rouesseau et al. 2007; Lambert et al. 2008). In the Northern Hemisphere, there is evidence that the Greenland ice-core isotopic signal is also mirrored in high-resolution tropical cave speleothems, such as in Hulu Cave, China (Wang et al. 2001). However, as with marine isotopes, environmental signals recorded by dust or oxygen/deuterium isotopes in ice cores may not always translate as an environmental signal in other types of sequences. Moreover, it is well established that there is asynchrony between ice-core records in the Northern and Southern Hemispheres, especially when considering shorter timescales. For example, millennial-scale events preserved in the Antarctic and Greenland ice cores are to some extent asynchronous, out-of-phase and sometimes opposite (Blunier et al., 1998; Steig and Alley, 2002; EPICA, 2006). This causes problems in using ice-core event stratigraphy for establishing a chronostratigraphy that can be compared across wide areas. Boundaries of chronozones should be isochronous, i.e. time-parallel (Björck et al. 1998). However, it would not be possible to define globally isochronous boundaries for a chronzone based on isotopic signals in either Greenland and Antarctica. In event stratigraphy the boundaries between events are not specifically designated and problems of time transgression that have arisen in applications of the terrestrial chronostratigraphy are no longer encountered (Björck et al. 1998, p. 289). In effect, this recognizes that ‘events’ can be diachronous.

Hughes and Gibbard (2015) recommended that event stratigraphy can, and indeed should, reside within a broader longer-term chronostratigraphical framework (such as the Late Pleistocene Subseries) and should not replace locally defined terrestrial chronostratigraphical frameworks. Indeed, Lowe et al. (2008, p. 7) recommended that ‘all site records should initially be designated using the appropriate local terminology, and that the timing and duration of local or regional climatic/environmental events be established independently of the ice-core record’. Once this is achieved, then correlations with the ice-core event stratigraphy are acceptable, and even desirable, when comparing records across wide areas. It has been shown that changes in the Greenland ice-core record are matched within independently dated speleothem records as far away as SE China (Cheng et al. 2006). However, intuitively, correlation with the Greenland ice-core record is likely to be most reliable for short time intervals (sub-millennial-, centennial- and decadal-scale changes) at high northern latitudes. For example, issues over diachronous environmental changes over the Late Pleistocene late-glacial interval have meant that locally defined terrestrial chronostratigraphies cannot be directly compared directly between regions (Lowe et al. 2019). In fact, most terrestrial records display spatial variation in response to global climate fluctuations, and changes recorded on land are often diachronous, asynchronous or both, leading to difficulties in global correlation. This is an evitable challenge to any attempts to link terrestrial records to a globally comparable or even hemispherically comparable records. In those cases where this has been attempted, such as the correlation of the global LGM with Greenland Stadial 3 in the Greenland ice-core records (Fig. 3), this represents a type of informal chronostratigraphy that is common to Quaternary science (e.g. Hughes and Gibbard 2015). In practice this approach is acceptable, but cannot replace formal chronostratigraphy. This has consequences for correlation since the widespread nature of diachronous boundaries in Quaternary climatostratigraphy means that the issue of correlation or comparison is a major and persistent question in Quaternary stratigraphy.

**Correlation or comparison?**

Correlation is fundamental to the construction of regional succession and, in turn, its relation to extra-regional or global scales throughout the geological column. To correlate is ‘to show correspondance in character and stratigraphic position between such geologic phenomena as formations or fossil faunas of two or more separated areas’ and correlation is defined as ‘demonstration of the equivalence of two or more geologic phenomena in different areas; it may be lithologic or chronologic’, according to the American Geological Institute’s Dictionary of Geological Terms (Bates and Jackson 1984, p. 113).

In this context, the question of the quality or strength of the correlation requires consideration. Where a terrestrial chronostatigraphy has been established, the means by which any particular deposit, event or similar entity can be related to a global scale, especially the marine isotope–stratigraphical divisions, arises. Today, in a wide range of cases where evidence for relating continental sequences or individual depositional units is weak or
even lacking, correlation may be attempted by comparison of curves or plots based on perceived interpretation of climatic changes from sedimentary or fossil assemblages, etc. Such a process may indeed show corresponding patterns of change which may be interpreted as demonstrating time equivalence. However, in reality this process cannot be termed ‘correlation’ (see above) unless concrete evidence is available to demonstrate the equivalence of the strata concerned. Instead it should more properly be termed ‘comparison’.

Comparison is ‘the act or instance of comparing; the quality of being similar’ (The Concise Oxford Dictionary 1976). Clearly any establishment of potential equivalence based on the latter is unreliable, since it is open to mis- or re-interpretation, and is likely to be unsafe. Indeed the danger of relying on the alignment of curves or plots to demonstrate the time equivalence of distant strata is that the process itself could potentially mask changes that, although following an apparently similar course, are not coeval but out-of-phase. An excellent example is illustrated when considering the boundary between the end of the last interglacial and the onset of the last cold stage in Europe. In the marine isotope record the start of the cold stage is placed at c. 115 ka based on a substantial cooling effect at this time (Shackleton et al. 2002, 2003). This is consistent with Lisiecki and Raymo (2005) who place the Marine Isotope Stage (MIS) 5d and 5e peaks (MIS 5.4 and 5.5) at 109 and 123 ka, respectively. However, the end of the Eemian Interglacial in Portugal, recognized in the palynological record in an offshore core, shows that the boundary is actually well within MIS 5d (Shackleton et al. 2003). The fact that the Eemian Interglacial does not correspond to the precise climatostratigraphical relationship suggested by MIS 5e envisaged by Shackleton (1969) was already noted by Sánchez-Goñi et al. (1999) who placed the end of the Eemian Stage Interglacial at 110 ka based on pollen in marine cores off Portugal. This important example highlights that there is a lag between terrestrial vegetational and the marine isotope records (see Turner 2002 for a discussion). Furthermore, there is also a lag between the timing of the end of the Last Interglacial between northern and southern Europe, with the elimination of forest occurring in the north at c. 115 ka whilst in the south tree populations persisted until c. 110 ka (Tzedakis 2003). This further emphasizes the caution needed in using the marine isotope record for correlating with terrestrial archives, and stage boundaries based on this archive are likely to be transient over millennial timescales.

The nature of the marine isotope succession

A further matter concerns the nature of the marine isotope succession itself. It is important to realize when comparing or attempting to correlate continental sequences with those on the ocean floor that isotope stratigraphy is not strictly a chronostratigraphy despite being referred to as such in some classic papers (e.g. Martinson et al. 1987). The nature of the marine isotope stratigraphy, its history and development and the consequent implications for chronostratigraphy are reviewed in Railsback et al. (2015) and explored below.

Isotope stratigraphy is a method of determining relative ages of sediments based on measurement of isotopic ratios of a particular element. It works on the principle that the proportions of some isotopes incorporated in biogenic minerals (calcite, aragonite, phosphate) change through time in response to fluctuating palaeoenvironmental and geological conditions. Oxygen isotopes, the most regularly applied for stratigraphy in the Quaternary, record...
detailed changes in ocean temperature and ice volume. In sediments, data from calcite microfossils, notably foraminifera, record fluctuating temperatures and the growth and decay of ice sheets, allowing the recognition of oxygen isotope stages (or more properly marine isotope stages). The isotope contents are controlled by temperature, global ice volume and salinity. Earlier papers (e.g. Shackleton 1967) assumed that benthic foraminiferal signals were thought to be largely unaffected by temperature (constant temperature of the world’s deep oceans) but this has since been shown to be over-optimistic (see Shackleton 2000; Skinner and Shackleton 2005). Elderfield et al. (2012) used Mg/Ca ratios in the benthic foraminifera to remove the temperature effects from the isotope measurements, to reconstruct a signal for global ice volume, and hence sea-level. Shakun et al. (2015) developed this concept and used a global compilation of 49 paired sea surface temperature–planktonic δ18O records to extract the mean δ18O of surface ocean seawater over the past 800 kyr, to separate out signals of global ice volume and global sea surface temperatures and then to model sea-level change. Because both global ice volume and sea-level parameters were driven by Milankovitch climatic cycles, it has been possible to identify and correlate marine (oxygen) isotope stages in detail across the globe, and δ18O curves provide a relatively refined (c. 6–20 ka resolution) timescale for Quaternary to Neogene time (Rawson et al. 2002). As such this is a form of astrochronology, and does produce ‘absolute’ numerical ages in the same way that top-down layer counting works with other media.

The critical point is that these marine (oxygen) isotope curves provide a continuous record of change and as such have come to represent the reference for correlation around the world (Railsback et al. 2015). Whilst there is no doubt that the record is fundamental to our understanding of broad ‘global-scale’ changes throughout the later Cenozoic, there are several substantial hurdles to correlation of these sequences to the land record. In chronostratigraphy substantial reliance is placed on the identification of boundaries, the basal boundary of each unit, be it the largest (erathem) to the smallest (chronozone) being defined from a specifically defined sediment sequence. For each unit only the base is defined, the top of a unit being defined by the base of that succeeding it. This allows for the addition of any missing time without the need to redefine units if intervening time is later identified.

However, in a quasi-continuous sequence, such as that represented by the marine isotope stratigraphy, it is difficult to determine where it is best to draw the stage boundaries. Ideally, the boundaries should be placed at the beginning point of a major climatic or environmental change. Railsback et al. (2015) discuss this issue in detail and noted that Emiliani (1955) explicitly conceptualized marine isotope stages as intervals of time with boundaries at changes in temperature. Both Emiliani (1961) and Shackleton (1969) implicitly but clearly followed that model with substages as successive contiguous intervals of time (Railsback et al. 2015). However, this is problematic because of the multifactorial nature of climate and the difficulty in identifying the point where the climatic change actually occurred on the plots. Since climatic events are only recognizable through the responses they initiate in depositional systems and biota, a compromise is required.

So where precisely are the stage boundaries? In principle in ocean-sediment sequences boundaries are placed on the plots at midpoints between temperature maxima and minima. The boundary points thus defined are assumed to be globally isochronous, but they are really graphic artifacts (Fig. 1), not necessarily reflecting actual changes at that point in time and space. On land temperatures may be very locally influenced and may also show a time lag in comparison to those indicated in the deep sea (see Railsback et al. 2015 and their figure 5). Dates for the MIS boundaries have been established based principally on orbital tuning (e.g. Martinson et al. 1987) a process that is accepted as valid within the limitations of the resolution achievable in these highly condensed sequences. However, the extremely slow sedimentation rate of ocean-floor deposits and the relatively rapid mixing rate of oceanic waters make high-precision correlation difficult. Nevertheless deep-ocean MIS records offer correlation with a resolution of a few thousand years or less within a particular marine basin. Drift deposits on the deep ocean floor may have significantly higher sedimentation rates which is why they are targeted for coring. Even in relatively low sedimentation rate deposits of the central North Atlantic, Ferretti et al. (2010) were able to extract a detailed isotope record of the Early to Middle Pleistocene boundary period MIS 19–21.

A further problem that arises from the definition of boundaries in ocean-sediment sequences is that the marine isotope stratigraphy adopted as a reference standard by the majority of workers is based not on a single-site, stratotype core but on a synthetic ‘stack’ of 57 globally distributed benthic δ18O sequences that have been ‘aligned using an automated graphic correlation algorithm’ (Lisiecki and Raymo 2005). This synthetic curve (Fig. 1) is intended to provide ‘a much needed common timescale and reference for comparison (correlation target)’. However, this single ‘ideal global’ marine isotope sequence is therefore not a chronostratigraphy since it synthesizes curves from around the world, i.e. it does not present a record from any one locality and therefore it infringes the practice and the rules of definition of chronostratigraphical units (Salvador 1994; Gibbard 2013). This problem was recognized by Shackleton et al. (1995) when they effectively observed single-type sequences for the isotope stages for the Late Pleistocene in core V28–238, from the eastern Pacific (Shackleton and Odycke 1973), while those defined in cores ODP 677 and 846 are those for the Middle Pleistocene and Pliocene, respectively (Shackleton and Hall 1989; Shackleton et al., 1995).

The problem with adopting a single standard marine isotope record is that it will contain local effects and analytical biases that must be recognized for correlation. An obvious worry is that if widely spaced core sequences are aligned statistically, any geographical variations in responses to climatic changes will be masked by the alignment process – a situation that is known to occur (cf. Skinner and Shackleton 2005). Moreover, if, as seems likely, most if not all climatic event boundaries are diachronous at durations of less than a few thousand years, the use of climatic events for worldwide fine-scale chronostratigraphical subdivision potentially becomes unsustainable over large areas (Moreno 2014; Rach et al. 2014; Hughes and Gibbard 2015), at least in the Late Pleistocene. The solution to this problem lies in the (re-)establishment of regional dated sequences in all environments, the inter-regional cross-correlation of which will highlight any variations in timing of events, the identification of which must be an important goal of ultra-high-resolution stratigraphy.

Comparison of sequences from the ice cores and the ocean isotope profiles serves to emphasize a further issue, the question of representation of short-term events within the larger-scale glacial–interglacial climate cycles. Clearly the ice-core records, especially those where the accumulation rate is sufficiently high, record considerably more detailed records of climatic events compared to those represented in the oceans. This is a consequence of accumulation, or more properly sedimentation rate, a factor which pervades the entire geological record.

Observations from modern processes indicate that sedimentation rates vary enormously depending on the environment of deposition, potentially by as much as 11 orders of magnitude (e.g. Sadler 1981), allowing for breaks in sedimentation. Whilst there is a hierarchy to this variation, modelling exercises (e.g. Crowley 1984) have demonstrated that as sedimentation rate decreases the number of timelines preserved decreases exponentially, and the completeness of the record of depositional events decreases linearly. The
consequence of this conclusion is that low-magnitude events are progressively eliminated from the sequence (Miall 1997, 2016), confirming the observation noted above. The implication of this is that the representation of the high-resolution events that occur on land or in the shallow marine environment are, in general, unlike to be recorded in the ocean sequences, providing a further hurdle to equating sequences in these disparate settings. Clearly exceptions will occur, including major influxes of sediment arising from drainage of major waterbodies or deposition of volcanic tephra, for example.

Further problems that arise in correlating continental and deep-water ocean sequences are the occurrence of bioturbation and sedimentary hiatuses in the latter. These two issues are intimately related and therefore can, for the sake of brevity, be considered together. It is frequently believed that the bottom environment of the deep sea is one of quiescence where sedimentary particles, including the remains of organisms, etc, gently rain down in an extremely slow but constant stream to accumulate and remain undisturbed. Whilst this may be true of certain regions, the presence of bottom-dwelling and burrowing fauna is well established, their activities giving rise tourbation or mixing of the surface sediments which blurs or attenuates the signal of environmental change (Manighetti et al. 1995; Anderson 2001). Generally, this disturbance is thought to penetrate to depths of 10–20 cm, a process that is regarded by palaecceanographers as of little significance for the long-term record. Although there is a demonstrably clear record of changes through the vertical sediment sequences, doubt must arise as to the precision that can be achieved in sequences where a sedimentation rate of a few centimetres or less in 1 ka occurs (Leeder 2011). This implies that the bioturbation depth spans the deposits of at least 3 ka or more, limiting the resolution to 20 ka or thereabouts in the majority of situations (McCave 1995). However Ferretti et al. (2010) have demonstrated that the effects of bioturbation are generally much less than previously assumed, following a programme of 1 cm sediment sampling from the central North Atlantic succession. Whilst abyssal plain sedimentation is certainly characterized by very fine-grained deposits, under certain circumstances hiatuses or substantial debris influxes can occur (Baldwin and McCave 1999). In particular, close to continental slopes or mid-ocean ridges, the input of substantial volumes of material by turbidity currents causes local erosion and recycling of accumulated pre-existing sediment. Equally adjacent to tectonically active regions sediment mixing is potentially possible associated with earthquake activity, submarine volcanism, the release of gases, etc. Submarine currents can give rise to resuspension and recycling of sediments in some situations. However, fortunately for general purposes, hiatuses of longer duration than the shortest-term Milankovitch cycles (i.e. c. 20 ka) are relatively rare in deep-water ocean sediments. For the purposes of astronomical time-scale construction, and medium-resolution palaeoclimatic and global stratigraphical studies, such records remain the best available (e.g. Pälike and Norris 2006; Smith et al. 2014).

Terrestrial–marine correlation: issues for understanding the nature of glacial cycles

Whilst the marine isotope record provides a very useful global reference timescale of the Quaternary (Fig. 1) the issues described in the previous section mean that its use as a record of global environmental change is more limited. Whilst the signal contains a global ice volume component it is a valuable proxy, so long as the leads and lags are understood. This has resulted in problems when correlating environmental changes recorded in different settings across the world. This is especially true at the local scale where local and regional environmental changes are often opposite or even out-of-phase with global environmental changes. The marine isotope record has long been considered to represent the key proxy for shifts between glacial and interglacial cycles at the global scale by virtue of the dominance of continental ice sheets on the isotopic composition of the oceans (Shackleton 1967). Whilst it is well known amongst palaecceanographers that the marine isotope record is more complex than just an ice-volume signal (Skinner and Shackleton 2005; Shakun et al. 2015), this is often overlooked by those working on terrestrial records. Moreover, it is apparent that the marine isotope record is misleading for correlations not only at the local and regional scales but also at the global scale. This has recently been highlighted when examining the nature of global glaciations through glacial–interglacial cycles (Hughes et al. 2013, 2020; Hughes and Gibbard 2018). Marine isotope records have been used to characterize the structure of glacial cycles. During the later Quaternary, they display a clear asymmetry though between interglacials with a slow descent into glacials and a rapid termination at their end (Broecker and van Donk 1970) (Fig. 1). This vision of ice-age cycles has driven the idea of global glacier maxima at the troughs of the marine isotope curve that has persisted for decades. However, as dating techniques have improved and become widely applied to date glacial successions around the world, it has become clear that the pattern of global glaciation does not match this paradigm. Until the late part of the 20th century it was notoriously difficult to date surface landforms and thus the legacy of even the most recent Late Pleistocene glaciation remained poorly dated and often indirectly interpreted from the basal ages of post-glacial sediment sequences. However, since the advent of cosmogenic exposure dating, which has become widely applied in the past 20 years to date landform surfaces, it has revolutionized our understanding of Late Pleistocene glaciation. This has also been paralleled by a dramatic increase in the dating of subsurface materials often closely related to glaciation especially through optically stimulated luminescence dating and to lesser extent cosmogenic nuclide depth profile dating. The mounting evidence has led to a shift in our understanding of the timing of the maximum extent of glaciations through the last glacial cycle, which equally has implications for understanding global glacier dynamics in earlier glacial cycles.

For the last glacial cycle (Late Pleistocene Subseries) the global glacial maximum has traditionally been placed at c. 1814C ka BP (c. 21 cal ka BP) based on the orbitally tuned marine oxygen isotope curve (e.g. Martinson et al. 1987; Lisiecki and Raymo 2005). However, as noted above, the marine isotope record has shortcomings for defining global glacier maxima. For example, for the Late Pleistocene Hughes and Gibbard (2015) argued that this is better defined in ice-core records and they correlated the global LGM with Greenland Stadial 3 (27.3–23.4 ka) (Fig. 3). This closely corresponds with sea-level minima dated independently from the marine isotope sequence using U-series techniques (Thompson and Goldstein 2006) and also the maximum extent of the Laurentide Ice Sheet (Balco et al. 2002; Ullman et al. 2015). Other ice sheets around the North Atlantic Ocean, such as the British–Irish ice sheet, also reached their maximum extent between 27 and 24 ka (Clark et al. 2012; Scourse et al. 2019), and ice sheets rapidly retreated and thinned soon after Heinrich Event 2 (Hughes and Gibbard 2015; Hughes et al. 2016). This illustrates that the
‘global’ LGM was driven by events in this region and, importantly, it is a regional rather than a truly global phenomenon. This further emphasizes the problems of correlation versus comparison when applying the marine isotope record to correlate fine-scale stratigraphical events in the Quaternary.

In addition to the problems of fine-scale correlations of global ice volume with events such as the LGM, the marine isotope record has more serious shortcomings when considering the overall pattern of global glaciations through glacial–interglacial cycles. The late trough in the glacial marine isotope stage record was for nearly 50 years assumed to correlate with the timing of the maximum extent of the large continental ice sheets, following the assumptions of Shackleton (1967). This assumption has dominated our perception of Quaternary glaciations for decades with the result that the concept of a global LGM has overwhelmingly influenced correlation of all kinds of terrestrial records for the Late Pleistocene. In effect it has essentially operated as a fixed tie point in Quaternary stratigraphy.

However, whether this tie point is real or imagined has recently been opened to question as more and more geochronological and fine-resolution stratigraphical evidence for global glaciations has been acquired. Hughes et al. (2013) examined the evidence for the timing of glaciations around the world and noticed that a large number of sites did not match the common concept of the global LGM. Many sites saw glacier maxima earlier in the last glacial cycle, sometimes by many tens of thousands of years. This situation was noted earlier by Gillespie and Molnar (1995) who observed that mountain glaciers in the mid-latitudes were asynchronous to the large continental ice sheets. However, Hughes et al. (2013) found that it was not just the mid-latitude glaciers that were asynchronous but some of the largest continental ice sheets reached their maxima at markedly different times to the global LGM indicated in the marine isotope record. Moreover, whilst the marine isotope record is known not to be a perfect mirror of global ice volume (Skinner and Shackleton 2005; Shakun et al., 2015), the general relationship was not doubted by Hughes et al. (2013) and Hughes and Gibbard (2018). Rather, it was the spatial and temporal representation of global ice volume that was questioned. This is because of the hugely dominant effect of changes in the volume of the Laurentide Ice Sheet on the marine isotopic composition of the global oceans. Nevertheless, this effect does limit the utility of the marine isotope record as a representative indicator of global glaciation and accompanying environmental changes, especially climatic changes, closely associated with glacier expansion and contraction in different parts of the world.

The problem of the marine isotope record and the pattern of global glaciation identified for the Late Pleistocene has major implications for understanding earlier glacial cycles. Hughes et al. (2020) took the lessons of the last glacial cycle and applied them to earlier glacial cycles in the Middle Pleistocene. It soon became apparent that similarities existed between some major glaciations, which were absent or different in extent from others. For example, in all glacial cycles there appeared to be the phenomenon of double glaciation maxima, early and late in the glacial cycles. In the glacial cycles characterized by the largest glacier global extents (such as MIS 16, 12 and 6 in the Middle Pleistocene, as well as the MIS 5d-2 in the Late Pleistocene), the second glaciation maximum corresponded closely to the global glacier maximum in the marine isotope record (LGM, Penultimate Glacial Maximum, etc.).

Conversely, in glacial cycles associated with weaker global glaciations (e.g. MIS 14, 10 and 8) the first glaciation maximum early in the glacial cycle was larger (Fig. 1). This is despite the marine isotope record suggesting the classic second and late glacial maximum was the largest. This is because the later peak represents the maximum of the Laurentide Ice Sheet but not other ice masses around the world. This highlights again that the saw-tooth asymmetry of the marine isotope record is misleading for understanding the nature of global glaciations and their extents.

New directions

In recent years several new techniques have been developed that offer the opportunity to clarify, re-examine or refine stratigraphical correlation. Here examples of these advances are reviewed.

One area that has advanced apace is Quaternary geochronology and associated dating techniques, which are considerably more diverse than for earlier periods of the geological timescale. Some of the techniques are applicable only to Quaternary deposits, while others can also be applied to older sequences. The time ranges of the major Quaternary dating methods over which each of the methods (after Pillans and Gibbard 2012) are shown in Figure 4. Quaternary dating methods have been summarized in several publications, and include Easterbrook (1988), Rutter and Cato (1995), Wagner (1998), Noller et al. (2000), Walker (2005), Elias (2007) and Elias and Mock (2013).

Continued advances in dating techniques hold great promise for the future but it is unlikely that alone they will overcome the serious correlation problems that are encountered in Quaternary continental sequences. This is especially true when using geochronological techniques for pre-Late Pleistocene deposits and landforms and even for fine-scale stratigraphical correlations in the Late Pleistocene and Holocene. Some of the most significant advances have occurred in radiometric dating which provide numerical ages (Fig. 4). Continuous developments and improvements in dating techniques mean that calculated ages change as new findings are made. For example, in cosmogenic exposure dating, production rates have been refined in recent years, such that for $^{10}$Be dating, the production rate has shifted by 20% from $c. 5$ to $c. 10^5$ atoms/gramme/annum, which has resulted in similar percentage increases in calculated exposure ages. For other nuclides, such as $^{36}$Cl, there is still significant disparity between different production rates, which means that exposure ages can vary by up to 24% (Allard et al. 2020). Other radiometric dating techniques are also occasionally affected by changes in calibration curves, such as for radiocarbon dating (e.g. Reimer et al. 2013) or changing values for isotope half-lives, such as in U/Th dating (e.g. Cheng et al. 2013). In addition to these issues all radiometric ages come with uncertainties associated with laboratory (internal) and systematic (external + internal) error (Schmitz 2012), although improvements in dating techniques in recent years mean that this is often just a few percent. However, all geochronological techniques rely on correct interpretation of the geological context and this is probably the biggest obstacle to correct correlation. In ideal situations multiple different dating techniques should be used to test and confirm geochronological frameworks that are subsequently used for correlation. Concerning the application of numerical dating, it is also important to remember that geochronology (geological time independent of the rock record), is a separate classification from chronostratigraphy (time based on representative rock sequences), the two schemes running in parallel.

Until very recently the principal and only practical means of displaying geology on the ground was the geological map. Whilst this remains an excellent means of recording, portraying and communicating several sets of two-dimensional information, it requires a significant amount of expert knowledge to interpret (Royle et al. 2012). However, recent advances in Geographical Information Systems, and three-dimensional modelling based on large datasets that have allowed them to be handled on desktop computers, have initiated a seed-change in the viewing, manipulation and interpretation of geological information (Jones et al. 2009). This is allowing construction of a new generation of geological models for onshore and offshore areas, including complex urban areas, such as London (e.g. Royle et al. 2012; Mathers et al. 2014) (Fig. 5). These models provide a means for integrating and visualizing evidence from many different sub-
disciplines, thus allowing a model to display more closely some of the natural heterogeneity of real geological systems. As well as allowing geoscientists to take account of the third dimension, in the near future models will be able to be manipulated to display changes through time (the fourth dimension). Nevertheless, the limitations of the data on which the assessments are based must be understood, as in all geological modelling exercises. As technological improvements allow workers to introduce greater levels of realism into their models, it is becoming more critical to describe accurately and to understand the nature of the sequences being investigated. The accuracy of these models depends not only on the density and quality of the original data, but also on the theoretical understanding of the underlying geology (Royse et al. 2012; Westerhoff et al. 2009).

Such a resource provides a fundamental tool for geological research, where the impact of individual geological or stratigraphical components on the sequences as a whole can be assessed, for example the interdependence of tectonics, sedimentation, stratigraphy, material properties and preservation.

Regarding the chronostratigraphical division of Quaternary time (Fig. 6), as Gibbard and West (2000, 2014) have noted, the current situation is unsatisfactory. This is because two partially compatible systems are being widely applied, yet neither is completely suitable for today’s knowledge of events. On the one hand, terrestrially based terminology, like that used in NW Europe (e.g. Mitchell et al. 1973) is still widely in use, whilst a significant number of articles have adopted the marine isotope nomenclature. As has been stated repeatedly, both these systems have limitations, but the potential difficulties of correlating (rather than comparing) with the ocean sequences in reality make the latter an unreliable enterprise (cf. Gibbard and West 2014). Direct correlation with the ocean or ice-core sequences holds a number of pitfalls, the greatest obstacle...
being the comparison of high-resolution discontinuous continental sequences with low-resolution yet quasi-continuous ocean basin sequences. Clearly a system is required that provides a solid foundation for stratigraphical division incorporating the modern understanding of events during the Quaternary, but which equally respects the rules...
and methodology of rigorous stratigraphical classification. The identification of additional events demonstrates the need to confront the definition of additional time divisions in the terrestrial sequence. Conversely, the uncritical adoption of the marine isotope stage sequence for division on the land begs the question: since the boundaries are imprecisely defined, should these divisions be adopted in the definition of high-resolution terrestrial sequences (cf. Gibbard and West 2014)? The shorter the duration of the changes the more acute the problem becomes. Land–sea correlation therefore remains the greatest challenge in chronostratigraphy of the late Cenozoic. Accurate land–ocean correlation ideally requires the identification of global markers, that can potentially be identified in the widest spectrum of environments.

How then are the equivalents of short-term event subdivisions to be reliably determined in ocean sediments? One possible means of addressing this problem is the application of new geomagnetic techniques, such as magnetic polarity stratigraphy that is based on the recognition of polarity zones in sediments. This, an approach resulting from the changes in the magnetic dipole field, is an independent phenomenon that can be recorded in the widest range of sedimentary records. The reversal horizons provide timelines for precise correlation at the reversal events. However in the last 20 years, relative geomagnetic palaeointensity (RPI) has been determined in a large number of investigations and holds potential for millennial-scale stratigraphical correlation within the relatively long-duration polarity chron. As Channell et al. (2009) have demonstrated, the association of some RPI minima with short magnetic excursions means that an RPI stratigraphy can now be established in the palaeomagnetic reversal record.

For the application of palaeointensity records to stratigraphy a calibrated reference profile (or profiles) must be developed. As for benthic oxygen isotopes (cf. Lisiecki and Raymo 2005), a sequence has been generated from multiple records which, although increasing the clarity of the signal, may average local variations by the statistical process (see above). The PISO-1500 stack, compiled by Channell et al. (2009), represents a stratigraphic reference profile spanning the last 1.5 ma, that can be used to correlate marine, lacustrine, loess and ice-core sequences (Fig. 7). This independent marine chronology could potentially eliminate difficulties inherent in oxygen isotope stratigraphy such as phase lags, and the assumption that δ18O is purely a glacial ice-volume or sea-level signal (Imbrie and Imbrie 1980; Skinner and Shackleton 2005). They speculate that potentially the timing and phase relationships of the climate system components may be resolvable independent of oxygen isotope stratigraphy, providing new insights into the mechanisms and timing of glacial–interglacial climate change and its correlation.

Reversals and excursions of the Earth’s geomagnetic field occur throughout the Quaternary and hold great potential for correlation across various environments, creating marker horizons that are readily detected globally in sedimentary and volcanic accumulations (Singer 2014). However, their application to correlation demands an accurate, high-resolution reference chronology for several main reasons. These include the potential to provide precise inter-correlation of the ocean and terrestrial sediment and ice-core records, which can be used to compare and contrast the timing and intensities of events from spatially distant regions. Of equal geochronological/stratigraphical importance is that the geomagnetic field instabilities associated with both reversals and excursions lead to enhanced production of cosmogenic isotopes. Therefore the application of cosmogenic isotopes for surface exposure dating or as chronostratigraphic markers requires a complete succession of geodynamo instabilities (e.g. Dreyfus et al. 2008; Singer et al. 2009). The timing of polarity reversals that define chronozone boundaries and the Geomagnetic Polarity Timescale, and the determination of the frequent excursions now known to have taken place during the intervals between the reversals offers a new potential means of high-resolution stratigraphy for regional, extra-regional and even land–sea correlation. This geomagnetic instability timescale for the Quaternary offers the potential for high-resolution chronostratigraphy (Singer 2014) (Fig. 8).
Fig. 8. The Geomagnetic Intensity Time Scale for the Quaternary period. The PISO-1500 palaeointensity record is taken from Channell et al. (2009) (cf. Fig. 6) (modified from Singer 2014). Reprinted from Quaternary Geochronology, Vol. 21, Singer, B.S., A Quaternary Geomagnetic Instability Time Scale, 29–52, Copyright 2014, with permission from Elsevier.
Conclusions

(1) Terrestrial stratigraphy comprises highly discontinuous, laterally variable, high-sedimentation rate sequences.

(2) A distinct characteristic of some terrestrial records is their surface expression, or geomorphology. However, these types of records are inherently fragmentary because of ongoing surface processes.

(3) Aside from extant ice sheets, the longest and best-preserved terrestrial records occur in stable basin settings, such as tectonic basins and extinct volcanic maars in areas beyond the influence of major erosional agents, such as the effects of Pleistocene glaciation. Except under these very exceptional circumstances, terrestrial sequences will never preserve a ‘complete’ record of events in a region.

(4) Nevertheless, as terrestrial organisms we are greatly concerned about terrestrial events and as such the records reconstructed from ocean sediments or ice cores will not replace land-based sequences.

(5) Not all investigations require the correlation of local sequences with those constructed from other environments, and in particular ‘global’ records, in order to be valid. In particular, researchers should avoid spurious correlation, such as correlating with marine isotope stages or other records when it is not necessary or appropriate for the investigation in question.

(6) The subdivision of high-resolution sequences from continental situations requires the application of systematic stratigraphical division (i.e. precise boundaries); the marine isotope stratigraphy potentially provides support and clarification with dating of successions, if not classification, especially when coupled with sequence stratigraphy.

(7) Correlation of land and deep-sea sequences requires the demonstration of the temporal equivalence of strata (i.e. isochronity), in terms of lithology, process, fossil content or time; comparison is not correlation. Where appropriate, onshore deposits can be traced seaward by seismic stratigraphy. The package of sediments (the sequence) produces a genetic equivalence, but a sequence boundary is an erosional surface; it is therefore likely to be diachronous.

(8) For example, the marine isotope record is not a good reflection of the spatial and temporal patterns of global glaciation. This is because the marine isotopic signal has been dominated by changes in the largest ice mass on Earth, the Laurentide ice sheet, whose influence masks the glacier ice signal from the rest of the world. This leads to erroneous correlations when glacial and other terrestrial records are compared with the marine isotope stratigraphy.

(9) Deep-sea profile sequences may provide a background template for ‘global’ comparison with the sequence events represented on land. However, these sediments are, in many places, limited in their time resolution and therefore their representation of short-term events of the type that often characterize terrestrial settings.

(10) Potentially diachronous boundaries or climatic events will not be recognized where synthetic profiles of multiple single-site sequences are used as global reference standards for climatic sequences.

(11) It is crucial that all Quaternary workers (regardless of background) fully understand the implications and the essential distinctions between the various subdivisions of rock strata if they are effectively to divide, correlate and reconstruct history from rock sequences.

(12) The basic principles required for subdividing the Quaternary sequence into chronostratigraphic units are the same as for other Phanerozoic chronostratigraphic units, although the methods of time correlation may have a different emphasis. As in the case of other chronostratigraphic units, those of the Quaternary require boundary definitions and designation of boundary stratotypes for all units defined for all environments.

(13) Recent advances in techniques, especially in geochronology and three-dimensional geological mapping, offer new insights into stratigraphical correlation. In addition, tools that can be applied across different sedimentary and volcanic situations to recognize events, such as palaeomagnetic reversals and excursions, hold great potential for refined chronostratigraphy and land–sea and land–ice correlations.

(14) These points reinforce the view that it is only through a carefully and systematically defined sequence of units for each region that a durable Quaternary geological timescale can be established and developed in the future.

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