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**Climatostratigraphy**

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**Figure 1** Fossiliferous sand deposits between tills exposed in the Cowden Burn railway cutting at Neilston in Renfrewshire, Scotland. From Geikie, J. (1874). *The Great Ice Age and Its Relation to the Antiquity of Man,* Figure 27. Isbister, London.

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Terminology

Before the impact of the ocean core isotope sequences, an attempt was made to formalize the climate-based stratigraphical terminology in the American Commission on Stratigraphic Nomenclature’s Code of Stratigraphic Nomenclature (1961), in which so-called geologic-climate units were proposed. A geologic-climate unit is based on inferred widespread climatic episodes defined from a subdivision of Quaternary rocks. Several synonyms for this category of units have been suggested, the most recent being climatostratigraphical units (Mangerud et al., 1974), in which an hierarchy of terms is proposed. In subsequent, stratigraphic codes, however (Hedberg, 1976; North American Commission on Stratigraphic Nomenclature, 1983; Salvador, 1994), the climatostratigraphic approach was discontinued since it was considered that for most of the geological column ‘inferences regarding climate are subjective and too tenuous a basis for the definition of formal geologic units’ (North American Commission on Stratigraphic Nomenclature, 1983, p. 849). As Gibbard and van Kolfschoten (2005) observed, this view does not find favor with Quaternary scientists since it is difficult to envisage a scheme of stratigraphical subdivision for recent Earth history that does not specifically acknowledge the climate change factor (Lowe and Walker, 1997). Accordingly, Quaternary stratigraphical sequences continue to be divided into geologic-climatic units based on proxy climatic indicators. Boundaries between geologic-climatic units were to be placed at those of the stratigraphic units on which they were based.

The American Commission on Stratigraphic Nomenclature (1961) defined the fundamental units of the geologic-climate classification as follows:

A ‘glaciation’ is a climatic episode during which extensive glaciers developed, attained a maximum extent, and receded. A ‘stadial’ (‘stade’) is a climatic episode, representing a subdivision of a glaciation, during which a secondary advance of glaciers took place. An ‘interstadial’ (‘interstade’) is a climatic episode within a glaciation during which a secondary recession or standstill of glaciers took place.

An ‘interglacial’ (‘interglaciation’) is an episode during which the climate was incompatible with the wide extent of glaciers that characterize a glaciation.

In Europe, following the work of Jessen and Milthers (1928), it is customary to use the terms interglacial and interstadial to define characteristic types of nonglacial climatic conditions indicated by vegetational changes, interglacial to describe a temperate period with a climatic optimum at least as warm as the present interglacial (Holocene, Flandrian) in the same region, and interstadial to describe a period that was either too short or too cold to allow the development of temperate deciduous forest or the equivalent of interglacial-type in the same region (West, 1977).

In North America, mainly in the United States, the term interglaciation is occasionally used for interglacial. Likewise, the terms stade and interstade may be used instead of stadial and interstadial, respectively (American Commission on Stratigraphic Nomenclature, 1961).

It will be readily apparent that although in long-standing usage, the glacially based terms are difficult to apply outside the glaciated regions for which they are defined. Moreover, Suggate and West (1969) recognized that the term glaciation or glacial is particularly inappropriate since modern knowledge indicates that cold rather than glacial climates has tended to characterize the periods intervening between interglacial events over most of the Earth. They therefore proposed that the chronostratigraphical term ‘cold’ stage be adopted for ‘glacial’ or ‘glaciation.’ Likewise, they proposed the use of the term ‘warm’ or ‘temperate’ stage for interglacial, both being based on regional stratotypes. Lütig (1963) also recognized this problem and attempted to avoid the glacial connotations by proposing the terms ‘cryomer’ and ‘thermommer’ for cold and warm periods, respectively. These terms have found little acceptance, however. The local nature of these definitions indicates that they cannot necessarily be used across great distances
or between different climatic provinces (Suggate and West, 1969; Suggate, 1974; West, 1977) or indeed across the terrestrial/marine boundary.

Perhaps the most significant decision in climate-based nomenclature regards where the boundaries should be drawn. Ideally, they should be placed at the climate change, but since the events are only recognized through the responses they initiate in depositional or biological systems, a compromise must be agreed upon. In practice, boundaries are generally placed at midpoints between temperature maxima and minima (e.g., in ocean sediment sequences) (Bowen, 1978). This positioning is arbitrary, but it is necessary because of the complexity of climatic changes. However, problems may arise when attempts are made to determine the chronological relationship of boundaries drawn in sequences of differing temporal resolution or sediment type, and indeed determined using differing proxies. In contrast, in temperate northwest Europe the base of an interglacial or interstadial is very precisely defined. It is placed at the point where herb-dominated (cold-climate) vegetation is replaced by forest. The top (i.e., the base of the subsequent glaciation or cold stage) is drawn where the reverse occurs (Jessen and Milthers, 1928; West, 1968). It is unclear, however, how this relates to the timing of the actual climate change recorded or how this is recorded by other proxies.

**Terrestrial Sequences**

The classical glacial–interglacial climate-based stratigraphy, before the advent of the ocean sediment sequence investigations, was overwhelmingly based on the identification of climatic events from terrestrial, coastal, and shallow marine sediment sequences. However, the recognition of climatic events from sediments is an inferential method and by no means straightforward. Sediments are not unambiguous indicators of contemporaneous climate so that other evidence, such as fossil assemblages, characteristic sedimentary structures (including periglacial structures) or textures, and soil development, must be relied on wherever possible to illuminate the origin and climatic affinities of a particular unit. Local and regional variability of climate complicates this approach in that sequences are the result of local climatic conditions, yet there remains the need to equate them to a global scale (Gibbard and van Kolfschoten, 2005).

In the second half of the 20th century, it was recognized that Quaternary time should be subdivided as far as possible in keeping with the rest of the geological column using time, or chronostratigraphy, as the basic criterion (van der Vlerk, 1959; Gibbard and West, 2000). Because stages are the fundamental working units in chronostratigraphy, they are considered appropriate in scope and rank for practical intraregional classification (Hedberg, 1976). However, the definition of stage-status chronostratigraphical units, with their time-parallel boundaries placed in continuous successions wherever possible, is a serious challenge, especially in terrestrial Quaternary climate-dominated sequences. In these situations, boundaries in a region may be time parallel, but over greater distances problems may arise as a result of diachronity. It is probably correct to say that only in continuous sequences that span entire interglacial–glacial–interglacial climatic cycles can an unequivocal basis for the establishment of stage events using climatic criteria be truly successfully achieved. There are additional problems that accompany such a definition of a stage, including the question of diachronity of climate changes and the detectable responses to those changes. For example, it is well-known that there are various ‘lag’ times of geological or biological responses to climatic stimuli. Thus, in short, climate-based units cannot be the direct equivalents of chronostratigraphical units because of the time-transgressive nature of the former.

In general practice today, these climatic subdivisions have been used interchangeably with chronostratigraphical stages by the majority of workers. Although this approach, which gives rise to alternating ‘cold’ and ‘warm’ or ‘temperate’ stages, has been advocated for 40 years, there remains confusion about the precise distinction between the schemes, some of which arises from a misunderstanding. It is essential to understand that a climatostratigraphical event, such as an interglacial or glacial, is not automatically assigned the status of a chronostratigraphical stage. This is simply a convention that has evolved from earlier classification schemes. As Zagwijn (1992) noted, it is impossible to assign each event to a separate stage now that we can identify so many and that it is clear that there are wide variations in their climate, duration, and scale. For example, the Netherlands’ Early Pleistocene Bavelian stage includes two interglacials and two glacials (De Jong, 1988; Zagwijn, 1992). Each of these interglacials is comparable in its characteristics to the last interglacial or Eemian, which is a discrete stage, also defined in The Netherlands. In these cases, workers have fallen back on the noncommittal term ‘complex.’ One example is the Saalian of Germany; originally defined as a glaciation (Fig. 1), this chronostratigraphical stage includes at least one interglacial, as currently defined (Litt and Turner, 1993).
Likewise, the Wanganui Basin sequence on the North Island of New Zealand, which includes evidence of multiple climatic events spanning the entire Pleistocene, has been assigned to only three (or four) chronostratigraphical stages (Pillans, 1991).

The original intention was that cold or warm or temperate stages should represent the first-rank climate oscillations recognized, although it has since been realized that most, if not all, are internally complex. Subdivision of these stages into substages or zones was to be based, in the case of temperate stages, on biostratigraphy and, in the case of cold stages, principally on lithostratigraphy and/or pedostratigraphy. Within the range of radiocarbon dating (ca. 30 ka), the most satisfactory form of subdivision is frequently that based on radiocarbon years. However, high-resolution investigations, such as those from ice cores, have allowed the recognition of ever more climatic oscillations of decreasing intensity or wavelength within the first-rank time divisions. These events are stretching the ability of the terminology to cope with the escalating numbers of names they generate. Terms such as ‘event,’ ‘oscillation,’ or ‘phase’ are currently in use to refer to short or small-scale climatic events (often referred to as ‘sub-Milankovitch oscillations’).

Ocean Sediment Sequences

Isotope studies from the bottom sediments of the world’s oceans, begun by Emiliani (1955) and developed by Hays et al. (1976), have indicated as many as 52 late Cenozoic glacial ages and that the continental evidence is so incomplete by comparison that terrestrial glacial–interglacial stratigraphy must depend on the ocean record for chronological foundation.

The marine oxygen isotope scale makes use of the fact that when continental ice builds up as a result of global cooling and sea level is lowered, the ice is depleted in $^{18}$O relative to the ocean water, leaving the ocean water enriched in $^{18}$O. The oxygen isotope composition of calcareous foraminifera and coccoliths, and of siliceous diatoms, varies in direct proportion to that of the water (Shackleton and Opdyke, 1973), which is itself a result of glacial ice volume variation. Emiliani’s (1955, 1966) original 16 stages, to which he applied the terms glacial and interglacial, were extended to 22 by Shackleton and Opdyke. Later development has seen extension of the sequence through the Early Pleistocene into the Neogene. Today, the sequence, shown in Figure 3, is a combination of measurements from cores V19–30, ODP677, and ODP846 (Crowhurst, 2002). The isotope stages recognized in core V28-238, from the eastern Pacific (Shackleton and Opdyke, 1973), are generally regarded as the ‘type’ for the later Quaternary, whereas those defined in core ODP677 and ODP846 are those for the Pliocene to Middle Pleistocene (Shackleton, 1989; Shackleton and Hall, 1989).

The events differentiated in isotope sequences are termed Marine Isotope Stages (MIS); this term is preferred by paleoceanographers to the previously widely used oxygen isotope stages. This is because of the need to distinguish the isotope stages recognized from those identified from ice cores or speleothem sequences (N. J. Shackleton, personal communication). The stages are numbered from the present day (MIS 1) backwards in time, such that isotopically heavy, cold-climate, or glacial events are assigned even numbers and isotopically lighter, warm, or interglacial (and interstadial) events are given odd numbers. Individual events or substages within marine isotope stages are indicated either by lowercase letters or in some cases by a decimal system. Thus, MIS 5 is divided into warm substages 5a, 5c, and 5e and cold substages 5b and 5d, or 5.1, 5.3, 5.5, and 5.2 and 5.4, respectively, named from the top downward. This apparently unconventional top-downward nomenclature originates from Emiliani’s (1955) original terminology and reflects the need to identify oscillations down cores from the ocean floor (Gibbard and van Kolfschoten, 2005).

A glance at the oxygen isotope sequences routinely obtained from ocean sediments reveals the complexity of the signal (Fig. 3), the nature of which becomes more complex with closer sampling or resolution in higher sedimentation rate profiles. The adoption of the simple glacial–interglacial alternation is in fact only a very generalized description for periods characterized by predominantly cold- or warm-climate isotopic ratios but that in reality show considerably more structure than can be accommodated in the geologic-climate terminology.

Although the marine isotope stratigraphy provides a continuous climateostratigraphy (at a certain resolution), it has not been formally defined as the chronostratigraphical yardstick for the later Cenozoic. This is because the ‘boundaries’ drawn between the marine isotope stages are not at fixed points in the sequences but at the points where the isotope plots cross the midpoints between maxima and minima. In other words, these boundaries are graphic artifacts, not natural events detectable in sediment sequences. The variability of the timing of the isotope stages in different cores is the result of a combination of this artifact and the impact of bioturbation, which together combine to limit the chronostratigraphical resolution of ocean-bottom sediment, except in rare anoxic situations. Therefore, it is not possible to use the isotope sequences for ‘golden-spike’ boundary definition (N. J. Shackleton, personal communication). A ‘date’ for the boundary between marine
isotope stages is therefore in reality rather difficult to determine, extrapolation being the only reliable way of achieving a relatively precise number.

**Land–Sea Correlation**

In recent years, it has become common to directly correlate terrestrial sequences with those in the oceans. This arises from a desire to correlate local sequences to a regional or global timescale, occasioned by the fragmentary and highly variable nature of terrestrial sequences. The realization that more events are represented in the deep sea, and indeed ice core sequences, than were recognized on land, together with the growth in geochronology, has often led to the displacement of locally established terrestrial scales. Instead, direct correlations of terrestrial sequences to the global isotope scale are advanced, but there are serious practical limitations to this approach (Schlüchter, 1992; Gibbard and van Kolfschoten, 2005).

In reality, there are very few means of directly and reliably correlating between the ocean and terrestrial sediment sequences. Direct correlation can be achieved using markers that are preserved in both rock sequences, such as magnetic reversals, radiometric dating, or tephra layers, and, rarely, fossil assemblages (particularly pollen). However, normally it is impossible over most of the record and in most geographical areas. Thus, these correlations must rely totally on direct dating or less reliably on comparison using the widely used technique of ‘curve matching.’ The latter can only reliably be achieved where long, continuous terrestrial sequences are available, but it is not straightforward because of overprinting by local factors. Moreover, the possibility of failure to identify ‘leads and lags’ in timing by the matching of curves is significant. In discontinuous sequences, which typify land and shelf environments, correlations with the ocean basin sequences are potentially unreliable in the absence of fossil groups distributed across the facies boundaries or potentially useful markers.

In recent years, the growth of stratigraphy recognized from short-duration, often highly characteristic events has led to attempts to use these features as a basis for correlation. This event stratigraphy (Lowe et al., 1999), typically changes of sea level, climatic oscillations or rhythms, and the like. These occurrences, often termed sub-Milankovitch events, may be preserved in a variety of environmental settings and thus offer important potential tools for high- to very high-resolution cross-correlation. Of particular importance are the so-called ‘Heinrich layers,’ which represent major iceberg rafting events in the North Atlantic Ocean. These detritus bands can potentially provide important lithostratigraphical markers for intercore correlation in ocean sediments, and the impact of their accompanying sudden coolings (‘Heinrich events’) may be recognizable in certain sensitive terrestrial sequences (summary in Lowe and Walker, 1997).

The term stadial has been adopted for these short-lived cold phases, whereas the intervening warmer phases are referred to as interstadials in the ice core sequences. Similarly, the so-called essentially time-parallel periods of abrupt climate change termed ‘terminations’ (Broecker and van Donk, 1970), seen in marine oxygen isotope profiles, can also be recognized on land as sharp changes in pollen assemblage composition or other parameters, for example, where sufficiently long and detailed sequences are available, such as in long lake cores. However, their value for correlation may be limited in high sedimentation rate sequences because these terminations are not instantaneous but have durations of several thousand years (Broecker and Henderson, 1998).

Of importance to the development of a high-resolution Quaternary stratigraphy is the precise recognition and timing of boundaries or events from the marine isotope stages on land and vice versa. Until very recently, this was not perceived as a problem since it had been assumed that boundaries identified using a variety of proxies on land were precisely coeval with those seen in ocean sediments. Yet different proxies respond at different rates and in different ways to climate changes, and these changes may be time transgressive. This has been demonstrated by work off Portugal by Sanchez-Goñi et al. (1999) and Shackleton et al. (2003), where the MIS 6/5 boundary has been shown to have not been coeval with the Saalian/Eemian stage boundary on land, as previously assumed (Gibbard, 2001). The same point concerns the MIS 1/2 boundary, which predates the Holocene/Pleistocene (Flandrian/Weichselian) boundary by approximately 2,000–4,000 years. Thus, boundaries recognized in high-resolution land sequences and low-resolution marine sequences cannot be assumed to be coeval.

**Future Potential**

Overall, the climate-based stratigraphical subdivision of the Quaternary has been remarkably successful in providing a framework for high-resolution stratigraphy, begun for terrestrial glacial sequences and today applied throughout the world to sediments from the widest range of environments, from mountains to ocean basins, ice cores, and loess sequences. It continues to be modified with the recognition of progressively smaller scale oscillations, and it is very likely that this will continue for the foreseeable future.
Despite criticism regarding the difficulty of interregional comparisons, it is obvious that the overriding influence of climate on natural processes will ensure that sequences will be subdivided climatically rather than on the basis of time, as applied throughout most of the preceding Phanerozoic. Therefore, for many Quaternary workers chrono- and climatostratigraphical terminology are interchangeable. The long-term goal should be to clarify the situation by continuing to develop a formally defined, chronostatigraphically based system that is fully compatible with the rest of the geological column, supported by reliable geochronology. However, this should ideally be determined using climate-based units defined from reference (stratotype) localities.

DATING OF QUATERNARY EVENTS

Dating of Quaternary events through astronomical (and subastronomical) cycles is clearly a geochronological tool of considerable future potential, already realized for the ocean and ice core sequences (Björck et al., 1998), and of singular importance to understanding rates of process operation on land once the problems of cross-facies correlation have been overcome. The way forward should be to date fixed events—probably magnetic reversals or major climatic events—as accurately as possible and then use the astronomical cyclicity to provide a finer scale chronology. There can be little doubt that in the future this scheme, based on the original concepts of climate-based subdivisions, will provide the fundamental chronology for Quaternary stratigraphy (Gibbard and van Kolschoten, 2005).

See also: Ice Core Methods: Overview; Chronologies. Paleocoeanography, Physical and Chemical Proxies: Oxygen Isotope Stratigraphy of the Oceans. Paleoclimate Modeling: The Last Interglacial. Paleoclimate Reconstruction: Sub-Milankovitch (DO/ Heinrich) Events. Quaternary Stratigraphy: Overview; Biostratigraphy; Chronostratigraphy; Lithostratigraphy; Pestostratigraphy.

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Introduction

Ever since Earth scientists started to study the Earth they have attempted to describe and classify their findings and communicate their observations. Since observations in Earth science deal with the properties of strata on top of each other (in outcrops or drillholes), these communications dealt with stratigraphy; i.e., the description of the observed layers of rock can be described in many ways, and so it happened, and still happens. Depending on the background of the Earth scientist, description and classification was at first based on fossil content (biostratigraphy) and/or lithology (lithostratigraphy). This was especially so in the eighteenth and nineteenth centuries. Advances in chemistry and physics in the twentieth century enabled other methods of classification of rocks (e.g., chemo-, chrono-, magneto-, and seismostratigraphic). Although this was a clear advance in geoscience it soon appeared that it also obscured clear communication. Fortunately, this was broadly understood and in 1976 the first edition of the International Stratigraphic Guide was published (Hedberg, 1976). This publication led the way to clarification of concepts and advancing knowledge in stratigraphy led to a second edition in 1994 (Salvador, 1994). Recent publications by Walsh (2005a–c) indicate the need for further clarification. This chapter is based on the principles of lithostratigraphic classification as defined by Hedberg (1976) and Salvador (1994), and the modifications proposed by Walsh (2005a). It is further based on the application of these principles on Quaternary deposits and on recent experiences in northwestern Europe (Bown, 1999; Gullentops et al., 2001; McMillan, 2002; 2005; Ebbing et al., 2003; Westerhoff et al., 2003; Rijsdijk et al., 2005, Weerts et al., 2005).

Lithostratigraphic Classification

What is Lithostratigraphy?

There are as many definitions of lithostratigraphy as there are textbooks. In short, lithostratigraphy is the classification of bodies of rock based on the observable lithologic properties of the strata and their relative stratigraphic positions (Hedberg, 1976; Salvador, 1994; Nichols, 1999). This implies that observable lithologic properties and stratigraphic position are the only criteria to be used when defining lithostratigraphic units. In the Quaternary record, the ‘rock’ is often not lithified. In many definitions of lithostratigraphy the concept of the study of outcrops is explicitly or implicitly present. Outcrops of Quaternary deposits are scarce and often short-lived in many regions. Furthermore, Quaternary deposits are absent or very thin in large parts of the world. Thickness, however, is no criterion in defining lithostratigraphic units (Hedberg, 1976; Salvador, 1994). Apart from that, the description of rock units or deposits encountered in drillhole can replace observations at outcrops. So, the general lithostratigraphic concepts can be applied to the Quaternary sedimentary record for...