of Africa; Mid-Pleistocene of Europe; Mid-Pleistocene of Southern Asia. **Vertebrate Studies**: Ancient DNA.

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Chronostratigraphy

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Introduction

Chronostratigraphy is the part of stratigraphy that deals with the relative time relations of rock bodies, and a chronostratigraphic unit is a body of rock that was formed during a specified interval of geological time (Salvador, 1994). (The use of the term 'rock' to describe Quaternary strata that are unconsolidated or semiconsolidated may seem inappropriate at first sight. However, such usage is consistent with that adopted by the International Stratigraphic Guide (Salvador, 1994), and thus the term 'rock' is used here in its broadest sense.)

To facilitate international communication, the rock record of the Earth is divided into standardized global chronostratigraphic units that make up the international Geological Time Scale (GTS), managed by the International Commission on Stratigraphy (ICS). No geological timescale can be final, and the GTS is continually being refined as new data become available. The latest iteration is GTS2004 (Gradstein *et al.*, 2004), which follows earlier iterations such as GTS1989 (Harland *et al.*, 1990) and GTS1982 (Harland *et al.*, 1982). The next iteration is planned to be GTS2008. Chronostratigraphic subdivisions of the Cenozoic Erathem are shown in **Figure 1**.

Each chronostratigraphic (time-rock) unit of the GTS has an equivalent geochronologic (time) unit (**Table 1**). This dual hierarchy means that geologists refer to the rocks of the Pleistocene Series, but events in the Pleistocene Epoch. Similarly the terms 'Early', 'Middle', and 'Late' are used as qualifiers for time units, while 'Lower' and 'Upper' are used as qualifiers for time-rock units. Zalasiewicz *et al.* (2004) have proposed to end the distinction between the two parallel classifications as a way of simplifying stratigraphic terminology. If their proposals were to be adopted, the terms Eonothem, Erathem, System, Series, and Stage would be become redundant, in favor of Eon, Era, Period, Epoch, and (disputably) Age. In addition, the qualifiers Upper and Lower would be made redundant in favor of Early and Late.

Global boundary Stratotype Sections and Points

International subdivisions of the Phanerozoic part of the GTS are defined by their lower boundaries at Global Stratotype Section and Points (GSSPs), often referred to as golden spikes. Note that a GSSP automatically defines the upper boundary of the underlying unit, thereby eliminating the possibility of overlap between adjacent units.

The principal requirements of a GSSP are:

1. Location in a stratigraphically continuous section.
2. Good exposure and easy access for further study.
3. Precise definition at a lithological marker horizon.
4. The presence of multiple criteria for global correlation.

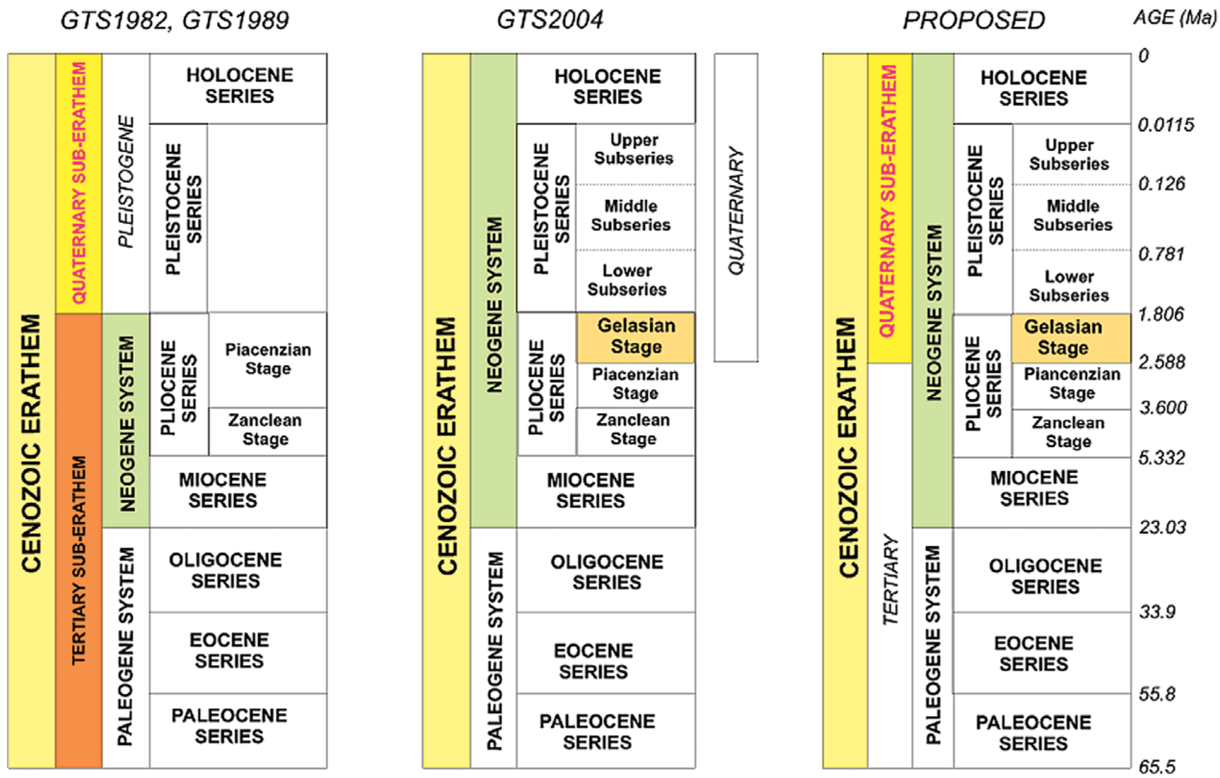

Figure 1 The evolving chronostratigraphic subdivision of the Cenozoic according to recent and proposed iterations of the international Geological Time Scale (GTS). Sources: GTS1982 (Harland *et al.*, 1982), GTS1989 (Harland *et al.*, 1990), GTS2004 (Gradstein *et al.*, 2004). For simplicity, stages of pre-Pliocene Series are not shown.

Table 1 Chronostratigraphic (time-rock) units of the GTS and their geochronologic (time) equivalents (Salvador, 1994)

Chronostratigraphic units	*Geochronologic units*
Eonothem	Eon
Erathem	Era
System	Period
Series	Epoch
Stage	Age

Typically, GSSPs have been defined in marine sedimentary sequences, to make use of marine biostratigraphic markers for global correlation. However, this is not a necessary requirement. Similarly, for reason of ease of access, no GSSP has yet been defined in drill core material. Both of these considerations will need to be fully assessed if the Holocene GSSP is defined in a Greenland ice core (see below).

Defining the Quaternary

The term Quaternary was introduced by the Italian mining engineer, Giovanni Arduino (1714–1795) when he distinguished four orders of geological strata – Primary, Secondary, Tertiary, and Quaternary (Schneer, 1969). However, its definition and usage in the modern sense was not really established until the XVIIIth International Geological Congress in London in 1948. At that conference it was resolved to select a stratotype for the Pliocene–Pleistocene boundary (stated as equivalent to the Tertiary–Quaternary boundary) and to 'place the boundary at the first indication of climatic deterioration in the Italian Neogene succession' (King and Oakley, 1949). After consideration of several sections over the next three decades, the Vrica section in Calabria, southern Italy was chosen and ratified as the Pliocene–Pleistocene stratotype (Aguirre and Pasini, 1985).

Unfortunately the formal definition of the Quaternary was left unresolved when Aguirre and Pasini (1985, p. 116) stated that 'The subject of defining the boundary between the Pliocene and Pleistocene was isolated from . . . . . . the status of the Quaternary within the chronostratigraphic scale'. The Quaternary was subsequently shown variously as a System above the Tertiary System (Salvador, 1994), or as a System above the Neogene System (Harland *et al.*, 1990), but was never formally ratified as such. In each case the base of the Quaternary (=base Pleistocene) was assigned an age of ~1.8 million years ago (Ma).

When the Quaternary was shown as an informal climatostratigraphic unit in GTS2004, the international Quaternary community was incensed, and much discussion ensued (e.g., Pillans and Naish (2004); Gibbard *et al.* (2005); Aubry *et al.* (2005)). A significant outcome was that a majority of Quaternary scientists favored a definition of the Quaternary with its base at ~2.6 Ma to encompass the time interval during which (1) the Earth's climate has been strongly influenced by bipolar glaciation, and (2) the genus *Homo* first appeared and evolved (Pillans and Naish, 2004). **Figure 2** summarizes the major temporal and latitudinal relations between orbital forcing and the Earth's late Pliocene–Early Pleistocene climate (3.0–1.5 Ma) as recorded by various records, including high-resolution deep-ocean $\delta^{18}O$ ice volume record from southwest Pacific ODP Site 1123, glacioeustatic cyclotherms of Wanganui Basin in New Zealand, ice-rafting as recorded by magnetic susceptibility at North Pacific ODP Site 882, a median grain size profile from Jingchuan loess section in China, and a pollen summary diagram from ODP 658 (offshore West Africa) showing progressive aridification. A steplike increase in African aridity about 2.8 Ma is linked to a significant event in hominid evolution in East Africa as the genera *Paranthropus* and *Homo* emerge from a single lineage (Pillans and Naish, 2004).

In August 2005, a joint ICS-International Union for Quaternary Research (INQUA) Task Group, which had been established to resolve the issue of how best to define the Quaternary, recommended that:

(1) The Quaternary be recognized as a formal chronostratigraphic/geochronologic unit.
(2) The lower boundary of the Quaternary should coincide with the base of the Gelasian Stage (~2.6 Ma), and thus be defined by the Gelasian GSSP.
(3) The Quaternary should have the rank of either System/Period above a shortened Neogene, or Sub-Erathem/Sub-Era within the Cenozoic and correlative with the upper part of an extended Neogene.

Quaternary Sub-Era

In September 2005, a meeting of the ICS recommended that the Quaternary be formally defined as a Sub-Era of the Cenozoic Era, and that its base be defined by the GSSP for the Gelasian Stage of the Upper Pliocene (see below). The ICS has submitted this recommendation to INQUA for their formal acceptance, and should this be forthcoming, ICS has requested that the Quaternary Sub-Era be formally ratified by the International Union of Geological Sciences (IUGS).

The Gelasian Stage (Upper Pliocene)

The Gelasian Stage is the youngest of three stages that make up the Pliocene Series. The GSSP for the Gelasian is located in the Monte San Nicola section (**Fig. 3**) near the town of Gela in Sicily (Rio *et al.*, 1998). It is defined at the base of the marly layer overlying sapropel Mediterranean Precession Related Sapropel (MPRS) 250, an organic-rich horizon with an astronomically calibrated age of 2.588 Ma (Lourens *et al.*, 1996; 2004). The Gauss/Matuyama paleomagnetic boundary occurs about 1 m (20 thousand years (ky)) below MPRS 250, and provides a close approximation for global correlation of the base of the Gelasian (= base of proposed Quaternary Sub-Era).

The Pleistocene Series

The GSSP for the Pliocene–Pleistocene boundary (= base Pleistocene) is located in the Vrica section, 4 km south of Crotone in Calabria, southern Italy (**Fig. 4**). The boundary is defined at the top of a sapropel layer 'e' (Aguirre and Pasini, 1985) with an astronomically calibrated age of 1.806 Ma (Lourens *et al.*, 1996, 2004). The boundary lies just above the top of the Olduvai Subchron, which facilitates global correlation.

Subdivision of the Pleistocene Series

Three working groups of the ICS are currently seeking suitable GSSPs to define the Upper, Middle, and Lower Pleistocene.

Lower Pleistocene

By definition, the GSSP for the Lower Pleistocene is the base Pleistocene GSSP at Vrica in southern Italy.

Middle Pleistocene

Participants in the Burg Wartenstein Symposium 'Stratigraphy and Patterns of Cultural Change in the Middle Pleistocene', held in Austria in 1973, recommended that the beginning of the Middle Pleistocene be defined to either coincide with, or be linked to, the Matuyama-Brunhes paleomagnetic reversal boundary

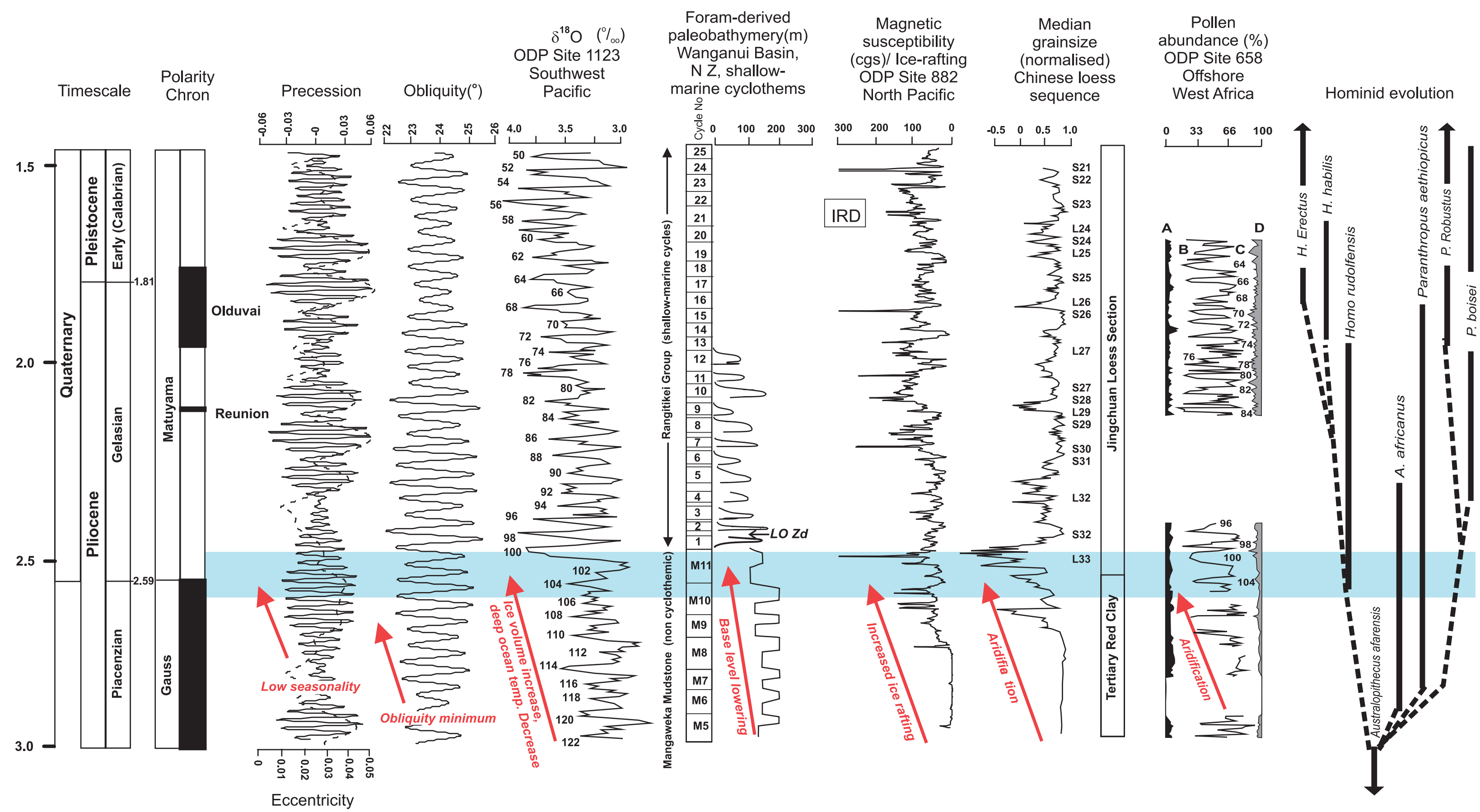

Figure 2 Summary of links between orbital forcing and paleoclimatic changes around 2.6 Ma that define the base of the Quaternary (from Pillans and Naish, 2004).

Figure 3 GSSP (arrow) for the Gelasian Stage of the Pliocene (Rio *et al.*, 1998), and proposed GSSP for the Quaternary Sub-Era. Image courtesy of International Commission on Stratigraphy.

Figure 4 GSSP (top of marker bed 'e') for the Pleistocene Series, Vrica section, southern Italy (Aguirre and Pasini, 1985). Image courtesy of International Commission on Stratigraphy.

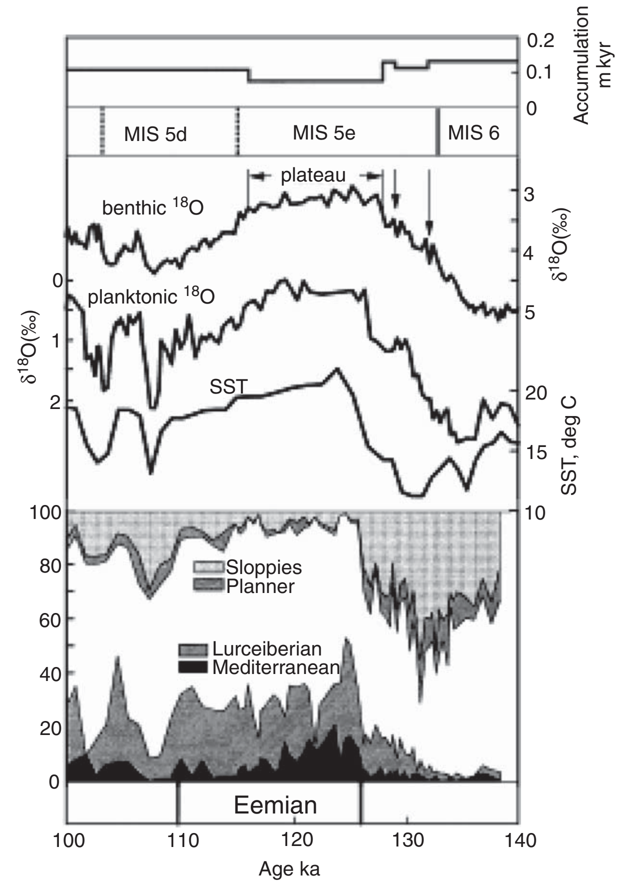

Figure 5 Marine and continental records of the last (Eemian) interglacial compared with MIS5e in marine core MD95-2024 (from Shackleton *et al.*, 2003).

(Butzer and Isaac, 1975). A similar recommendation was made by the INQUA Working Group on Major Subdivision of the Pleistocene at the XIIth INQUA Congress in Ottawa in 1987 (Richmond, 1996), and although potential GSSPs in Japan, Italy, and New Zealand were discussed, no decision was reached. Pillans (2003) also advocated the Matuyama-Brunhes boundary (MBB), because it constitutes the most recognizable chronostratigraphic marker in weathered continental deposits.

At present the Subcommission on Quaternary Stratigraphy (SQS) Working Group on the Lower–Middle Pleistocene Boundary is considering candidate sections in Italy and Japan, having resolved at the XXXIInd International Geological Congress in Florence in 2004 to place the boundary as close as possible to the MBB.

Upper Pleistocene

The Middle–Upper Pleistocene boundary is generally placed at the beginning of the Last (Eemian) Interglacial or the beginning of MIS5, with an age of ~130 ky (Gibbard, 2003). However, detailed pollen analyses of marine cores to the west of Portugal have shown that the base of MIS5 is significantly earlier (~6 ky) than the base of the Eemian (Shackleton *et al.*, 2003; **Fig. 5**). Gibbard (2003) has argued that the Upper Pleistocene GSSP should be chosen in a high-resolution terrestrial sequence at the base of the Eemian, and he nominates a depth of 63.5 m in the Amsterdam Terminal borehole as a candidate GSSP.

Holocene Series

The base of the Holocene Series (= top of Upper Pleistocene) is broadly accepted as the end of the last glacial period, with an age of 10,000 radiocarbon years (^{14}C years). However, this definition has never been ratified by the ICS. A recent proposal by a working group of SQS has recommended that the GSSP be defined at a depth of 1,492.3 m in the NGRIP ice core from Greenland, reflecting the first signs of climatic warming at the end of the Younger Dryas. The age of the boundary, based on multiparameter annual layer counting is 11,734 cal ^{14}C years before present (BP) If ratified, this GSSP would be the first to be defined in an ice core.

Local Chronostratigraphic Units and Timescales

In most regions of the world, fossils remain the principal means of establishing the age and sequence of Phanerozoic rocks, including many Quaternary deposits. However, while it is generally possible, using biostratigraphy, to correlate deposits with the major chronostratigraphic units of the GTS at Series level and above, regional endemism of biota often prevents correlation at finer scales (e.g., Stage level). Establishment of local timescales is a solution to this problem.

Numerous local 'timescales' have been erected for regional subdivision of the Quaternary, but the majority of these are, strictly speaking, climatostratigraphic units, not chronostratigraphic units. Furthermore, few of the regional stages have been formally defined using Local boundary Stratotype Sections and Points (LSSPs). A notable exception is in New Zealand, where most Cenozoic local stages are defined (or are in the process of being defined) by LSSPs in marine sequences. These include the New Zealand Haweran, Castlecliffian, and Nukumaruan Stages with LSSPs in Wanganui Basin (Cooper, 2004).

The need for local timescales is increasingly debated; however, in relatively isolated regions such as New Zealand, so long as fossils remain the principal means of correlation, it seems likely that local timescales will be required.

Chronostratigraphic Markers

A chronostratigraphic horizon or marker is a stratigraphic surface that is everywhere of the same age (Salvador, 1994). Although they are theoretically without thickness, in practice the term chronostratigraphic horizon (or chronohorizon) has been applied to very thin and distinctive markers that are essentially the same age over their whole geographic extent. Examples of chronostratigraphic markers in the Quaternary include tephras, magnetic polarity reversal horizons, and tektites. The latter are glassy objects produced from melted crustal rocks that are caused by large hypervelocity meteorite impacts. About 800,000 years ago a large extraterrestrial impact occurred in southeast Asia, producing tektites which are found over a wide area, including much of Australia and surrounding oceans – these are usually referred to as Australites or Australasian tektites. Zhou and Shackleton (1999) used the Australasian tektite layer to demonstrate the misleading position of the MBB in Chinese loess, concluding that there was a time delay in remanence acquisition in the loess and a downwards displacement of the apparent position of the MBB. Such a study is a pertinent reminder that magnetic reversal boundaries are not everywhere isochronous.

Finer Subdivision of the Quaternary using Marine Isotope Stages

Oxygen isotope records, based on analysis of foraminifera in deep-sea cores, have been divided into MIS, numbered from the top downwards (**Fig. 6**). Because the $\delta^{18}O$ signal dominantly reflects changes in the oxygen isotopic composition of the global ocean, the stages have been used to provide a framework for global correlation of marine cores, limited only by the mixing time of the ocean and deep-sea sediment biotubation rates. Indeed, as Shackleton and Opdyke (1973, p. 48) famously predicted: 'Thus it is highly unlikely that any superior stratigraphic subdivision of the Pleistocene will ever emerge'.

MIS are numbered so that odd numbers correspond with $\delta^{18}O$ minima (interglacial stages) and even numbers correspond with $\delta^{18}O$ maxima (glacial stages). MIS1 corresponds to the present interglacial period and stages are numbered sequentially down to MIS103 at the base of the Quaternary (**Fig. 6**), and beyond.

MIS boundaries are placed at points of maximum change between maxima and minima. However, additional events (maxima and minima) have been identified and numbered within many stages. Prell *et al* (1986) introduced a numbering system for these events whereby, for individual isotopic events within any stage, the integer portion of the code represents the MIS number, and decimal number refers to the event. As in MIS nomenclature, even number decimals refer to $\delta^{18}O$ maxima, and odd number decimals refer to $\delta^{18}O$ minima. Thus, event 5.5 is the lower interglacial event in MIS5 corresponding to Stage 5e of Shackleton and Opdyke (1973). In the same way, upper MIS boundaries are assigned a zero decimal, so event 5.0 corresponds to the MIS4/5 boundary.

Although not representing true chronostratigraphic horizons, MIS and isotopic events are widely used as such, particularly for correlation between

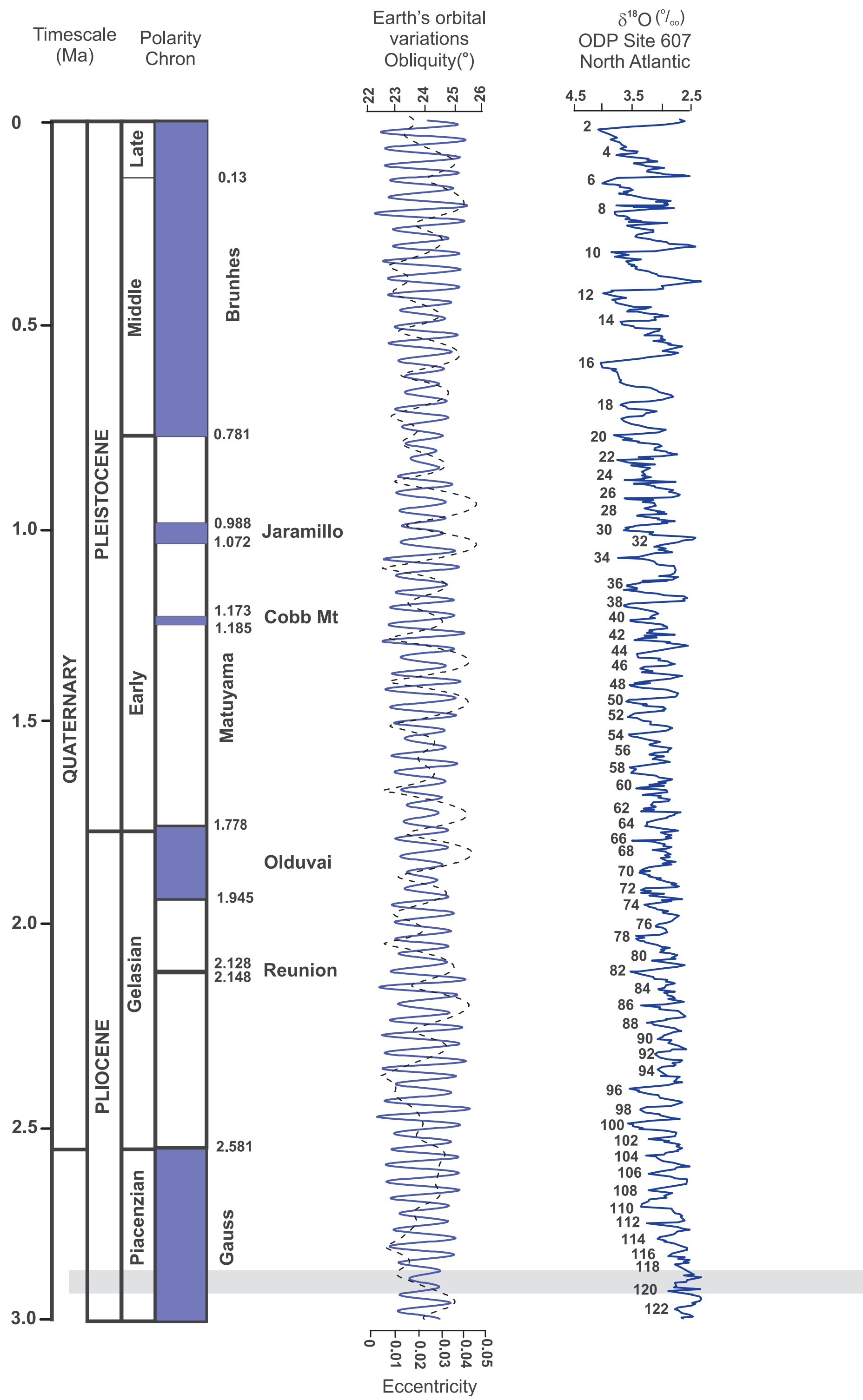

Figure 6 Chronostratigraphic units, paleomagnetic datums, and ages (from Lourens *et al.*, 2004) for the Quaternary. Orbital variations in obliquity and eccentricity from Berger and Loutre (1991). Oxygen isotope record from ODP Site 607 from Raymo *et al.* (1989). Adapted from Pillans and Naish (2004).

deep-sea cores. Furthermore, they are frequently used for correlation between marine and terrestrial sequences, a practice that ignores the likely leads and lags between marine and terrestrial indicators of past environmental change (c.f., the ~6 ky estimated offset between the pollen and isotopic records of MIS5.5 recorded in cores off the coast of Portugal by Shackleton *et al.* (2003)).

Astronomical Timescale

Prior to 1950 and the development of modern radiometric dating techniques such as radiocarbon, Quaternary chronology was rather speculative. Early attempts to infer ages for various glacial deposits using the chronology of orbital variations and resultant solar insolation curves (calculated by Milankovitch and others) were greeted with some skepticism. However, in the late 1960s and early 1970s, the astronomical chronology received strong support from dated coral reef sequences in New Guinea and Barbados (e.g., Broecker *et al.* (1968)). However, it was Hays *et al.* (1976) who provided the first convincing evidence that the independent contributions of all three orbital elements (obliquity, precession, and eccentricity) could be recognized in the geological record.

Today, the astronomical chronology of deep-sea cores is highly developed, and based on astronomical calibrations, the ages of all isotope stages, and magnetic reversals in the Quaternary (and much of the Neogene) are well established (e.g., Shackleton *et al.* (1990); Lourens *et al.* (1996); see **Figure 6**). Astronomical calibration of marine sequences in the Mediterranean provides highly precise numerical ages for individual sedimentary cycles, including the Pleistocene and Gelasian (= Quaternary) GSSPs (Lourens *et al.*, 2004). Astronomical calibration of the shallow marine sedimentary record from the Wanganui Basin in New Zealand has also been completed for the entire Quaternary (Naish *et al.*, 1998; and updated by Pillans *et al.*, 2005), and provides the primary chronology for LSSPs of the New Zealand Quaternary stages (Cooper *et al.*, 2004).

Abbreviations

BP	before present
^{14}C	carbon-14
GSSP	Global Stratotype Section and Point
GTS	Geological Time Scale
ICS	International Commission on Stratigraphy
INQUA	International Union for Quaternary Research
IUGS	International Union of Geological Sciences
LSSP	Local boundary Stratotype Sections and Points
Ma	million years ago
MBB	Matuyama-Brunhes boundary
MIS	Marine Isotope Stage
MPRS	Mediterranean Precession Related Sapropel
NGRIP	North Greenland Icecore Project
SQS	Subcommission on Quaternary Stratigraphy

See also: **Glaciation, Causes**: Milankovitch Theory and Paleoclimate. **Paleoceanography, Physical and Chemical Proxies**: Oxygen Isotope Stratigraphy of the Oceans. **Quaternary Stratigraphy**: Overview; Tephrochronology.

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Climatostratigraphy

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In contrast to the rest of the Phanerozoic, the Quaternary has a long-established tradition of sediment sequences being divided on the basis of represented climatic changes, particularly sequences based on glacial deposits in central Europe and mid-latitude North America. This approach was adopted by early workers for terrestrial sequences because it seemed logical to divide till (glacial diamicton) sheets and nonglacial deposits or in stratigraphical sequences into glacial (glaciation) and interglacial periods, respectively (West, 1968, 1977; Bowen, 1978). The divisions were therefore fundamentally lithological (**Fig. 1**). The overriding influence of climatic change on sedimentation and erosion in the Quaternary has meant that, despite the enormous advances in knowledge during the past century and a half, climate-based classification has remained central to the subdivision of the succession. Indeed, the subdivision of the modern ocean sediment isotope stage sequence is based on the same basic concept. The following discussion is modified from a review by Gibbard and van Kolfschoten (2005).

For at least the first half of the 20th century, the preferred scale was that developed for the Alps at the turn of the century by Penck and Brückner (1909), although evidence for multiple glaciation (in contrast to previous monoglacialist concepts) and intervening warmer climate interglacial events had already been proposed by Geikie (1874) (**Fig. 1**). The Alpine scheme (**Fig. 2**) was based on the identification of glaciofluvial accumulations that could be traced upstream to end moraines that marked maximum glacial extent positions in the Alpine foothills of southern Germany. The terrace surfaces developed on the glaciofluvial sediments were immediately underlain by fossil soils that were related by Penck and Brückner to interglacial weathering intervening between the glaciations. These observations provided the foundation for alternating glacial–interglacial

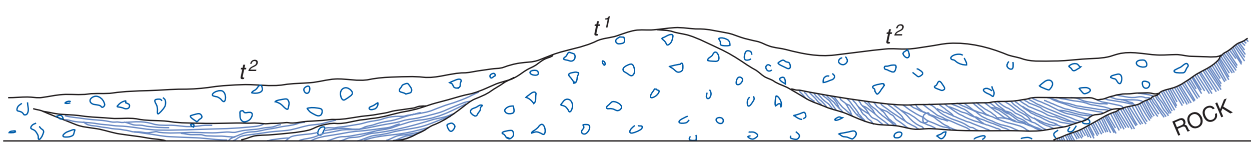

Figure 1 Fossiliferous sand deposits between tills exposed in the Cowden Burn railway cutting at Neilston in Renfrewshire, Scotland. From Geikie, J. (1874). *The Great Ice Age and Its Relation to the Antiquity of Man*, Figure 27. Isbister, London.

	Alps	Northern Europe	North America	European USSR
Authors	Penck & Brückner (1909–11)	Woldstedt (1926)	Flint (1957)	Flint (1957)
Glacial	Würm	Weichsel	Wisconsin	Valdai
Interglacial	Riss/Würm	Eem	Sangamon	Mikulino
Glacial	Riss	Saale	Illinoian	Moscow/Dneipr
Interglacial	Mindel/Riss	Holstein	Yarmouth	Lichvin
Glacial	Mindel	Elster	Kansan	Oka
Interglacial	Günz/Mindel	Cromer	Aftonian	Muchkap
Glacial	Günz		Nebraskan	?

Figure 2 Penck and Brückner's (1909) scheme of glaciations (and interglacials) in the Alpine region, compared to those proposed for other regions of the Northern Hemisphere.