The Quaternary

In late July 2007, some 1100 Quaternary scientists gathered for a week-long conference in the tropical city of Cairns in northeast Australia for the 17th quadrennial congress of the International Union for Quaternary Research (INQUA). Conference presentations were on topics in such diverse fields as archaeology, stratigraphy, geomorphology, palaeontology, geochemistry, hydrology, climate change and geochronology. To an outsider, the unifying theme of an INQUA Congress may be difficult to grasp, but diversity has always been a characteristic of Quaternary research, more so than for any other major period of the geological time scale.

The volume and breadth of Quaternary research can be gauged by the fact that there are four major international journals in the English language that include Quaternary in their titles, each containing exclusively Quaternary material: *Quaternary International, Quaternary Research, Journal of Quaternary Science and Quaternary Science Reviews*, the latter having one of the highest impact factors of any earth science journal. Two other journals in English, *Boreas* and *The Holocene* also contain exclusively Quaternary material, as do several journals in non-English languages, e.g. *Géographie physique et Quaternaire* (French, Canada), *Quaternaire* (French), *Eiszeitalter und Gegenwart* (German), *Il Quaternario* (Italian) and *Cuaternario y Geomorfologia* (Spanish). There is also a recently published Encyclopedia of Quaternary Science (Ed. S. Elias) in 4 volumes and over 3000 pages which is an excellent up-to-date source of information on the Quaternary. It is also worthy of note that, in 2007, INQUA became a full member union of the International Council for Science, the only geological time period to have its own union.

This Special Issue of *Episodes* contains a selection of papers that we hope will convey to readers something of the diversity of Quaternary research, with 15 papers grouped according to 4 major themes:

1. *Humans and the Quaternary*. As highlighted in the papers by Clague and Dennnell, although the Quaternary spans only a fraction of the 4.5 billion years of Earth history, it is disproportionately important because it is the interval during which humans evolved and because it includes the present. In both these papers we are reminded of the powerful influence of climate change on human activities, including those of the past, present and future.

2. *Quaternary stratigraphy*. The Quaternary has long been known as the period of the ice-ages, though, as discussed by Ehlers & Gibbard, we now know that evidence of Cenozoic glaciation extends well beyond the Quaternary. Similarly, Dodonov & Zhou demonstrate that while loess deposits in Asia represent one of the most complete continental records of the Quaternary, loess deposition has a history that extends back to the Miocene. However, compared to earlier geological periods the Quaternary offers better preservation of strata and greater stratigraphic resolution. Nowhere is this more evident than in ice cores from Antarctica which, as shown by Wolff, provide a detailed palaeoclimate record extending back some 800,000 years. The high- to ultra-high-resolution record of rapid, global environmental changes, described by Hoek, that accompanied the transition from the last glacial to the present interglacial period, is an excellent example of the multi-disciplinary nature of Quaternary research. A global perspective on Quaternary stratigraphy is provided by Gibbard & Cohen, centred on their chronostratigraphic correlation chart of the last 2.7 million years.

3. *Definition of the Quaternary*. Despite its long use as a chronostratigraphic subdivision of geological time, the formal definition of the Quaternary remains contentious including its duration and rank. In 2007, at the 17th INQUA Congress in Cairns, the general assembly of several hundred delegates unanimously supported the definition of the Quaternary as a Period/System with its base defined at the GSSP of the Gelasian Stage (~2.6 Ma). The paper by Ogg & Pillans, the two papers by Head, Gibbard & Salvador and that by Lourens explore several scenarios for defining the Quaternary, recognising that the definition cannot be divorced from considering the definitions of the Pleistocene, Neogene and Tertiary. This will be a major topic of discussion at the 33rd International Geological Congress in Oslo in August 2008.

4. *Subdivision of the Quaternary*. Unlike the Pliocene and earlier epochs of the Geological Time Scale (GTS), there are currently no formally defined stages of the Pleistocene and Holocene. However, the Pleistocene has long been divided into Lower (Early), Middle and Upper (Late) Subepochs and there is renewed impetus to define formally stages within these subepochs. The paper by Cita summarises recent work towards defining Italian regional stages for the Pleistocene that could be adopted as international stages. The papers by Head, Pillans & Farquhar, Litt & Gibbard and Walker et al describe the progress of three working groups of the ICS Subcommission on Quaternary Stratigraphy towards defining formal Global Stratotype Sections and Points (GSSPs) for the Middle Pleistocene Subseries, Upper Pleistocene Subseries and the Holocene Series, respectively. The base of the Lower Pleistocene Subseries corresponds to the base of the Pleistocene and therefore is defined automatically by the latter. The proposal of Walker et al to define the Holocene GSSP in a Greenland ice-core is unique in the GTS. The Holocene is also the only remaining epoch in the GTS to be formally defined.

The editors would like to thank the many people who have made this special volume of papers possible. In particular we thank Jim Ogg for proposing the project, all the contributors and referees, and finally the *Episodes* Editor Zhenyu Yang and his staff for their tolerance and support that enabled us to produce this publication.

Philip Gibbard and Brad Pillans

by John J. Clague

Importance of Quaternary research to society

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The Quaternary Period, although only an instant in the 4.5 billion year expanse of geologic time, is disproportionately important because it is the interval during which humans evolved and because it includes the present. Events of the Quaternary are preserved in sediments, ice sheets, and landforms with a greater degree of completeness and temporal resolution than those of any earlier period of comparable length. Studies of these historical and environmental archives continue to provide the essential context that allows scientists to evaluate what is happening with Earth's climate today and to clarify our vulnerability to hazardous natural processes, for example earthquakes, tsunami, volcanic eruptions, floods, and landslides.

Introduction

The Quaternary Period is unique among all divisions of geologic time in that it includes the present day—the instant in the 4.5 billion years of Earth history that most preoccupies humans. Most humans have little sense or appreciation of recent history, and even less so of geologic history. As they look back in time, humans become increasingly disconnected from it. They have considerable interest in events of the past several years to several decades, less interest in events hundreds to thousands of years ago, and, with some exceptions, almost no interest in events millions or billions of years old. It is perhaps for this reason that humans relate to the research of Quaternary scientists, dealing as it does with processes and effects closest to their temporal frame of reference. This fact is not lost on Quaternary scientists - much of the intellectual energy in our community is channelled into societally relevant, earth science issues to which we can bring our skills to bear.

Geologists working far deeper in geologic time likewise have much to offer society, but they commonly are interested in processes and effects that are cumulative, spanning millions to tens of millions of years. The unavoidable incompleteness of the geologic record generally precludes detailed reconstructions of "old" events, at least on timescales that are relevant to most people. Quaternary scientists deal with sediments and landforms that are young, commonly more complete, and resolvable at decadal to centennial timescales.

This paper highlights and amplifies on these comments by discussing two of the key issues confronting humanity today—climate change and hazardous Earth processes. Because my space is limited, I can only touch on the many contributions that Quaternarists are making in even these two areas and not at all on their contributions to other important public issues. My goal is to convey the rapid advances that are being made by a diverse and growing group of scientists united under the umbrella of the "Quaternary".

Climate Change

Al Gore and the International Panel on Climate Change (IPCC) have moved climate change to the forefront of the public agenda. As *An Inconvenient Truth* so graphically depicts, the signs of a change in climate are ubiquitous and well known—warmer surface temperatures, shrinking glaciers, diminishing Arctic sea ice, rising seas, and ecosystems under stress, to name a few. The focus within the scientific community has been, and continues to be, on forecasting climate change caused by increases in atmospheric carbon dioxide, methane, and other greenhouse gases over the remainder of this century. The research is being done principally by atmospheric scientists using highly sophisticated computers and numerical models.

Climate models are only reliable, however, if they fully capture the incredible complexity of the climate system, which I would argue is not yet the case. Furthermore, the models must be validated with historic climate data and, where possible, with reliable proxy climate data that can be provided only by Quaternary scientists. Finally, Quaternary scientists are perhaps in the best position to explain to the public and policy makers that climate change is the norm, that natural phenomena drive climate change, and that it is essential to disentangle natural from human-induced changes in the climate system.

Critical contributions to understanding Earth's climate have been made by oceanographers studying deep-sea sediments and glaciologists working on long cores taken from the Greenland and Antarctic ice sheets. Beginning with the pioneering work of Emiliani (1955) and later that of Shackleton (1967), Dansgaard and Tauber (1969), and Shackleton and Opdyke (1973), Quaternary scientists came to recognize the close linkage between Earth's atmosphere and its oceans, the important role of ocean bottom water in redistributing energy on the planet, and the rapidity of changes in Pleistocene climate and sea level. Scientists documented major restructurings in climate that happened on timescales of decades, such as during the Younger Dryas interval (12,700–11,500 years ago) at the end of the Pleistocene (Broecker and Denton, 1990).

Insights into the Earth system provided by Quaternary oceanographers in the 1960s and 1970s encouraged scientists to exploit another climate proxy—the Greenland and Antarctic ice sheets. Late Quaternary oxygen-isotope records with annual to decadal resolution have now been obtained from ice cores at more than 100 sites in Greenland and Antarctica, as well as from ice caps in the Himalayas (Thompson et al., 1989), the Andes (Thompson et al., 1995) and on Mt Kilimanjaro in Africa (Thompson et al., 2002). These records have provided an unparallel window into Earth's climate extending back to nearly 800,000 years (Figure 1; Johnsen et al., 1972; Lorius et al., 1979; Dansgaard et al., 1982, EPICA Community Members, 2004; Siegenthaler et al., 2005; Sphani et al., 2005). The Greenland ice cores provide evidence for periodic cold events that last about 1,000 years and begin and end abruptly. Broecker and Denton (1990) referred to these events as Dansgaard-Oeschger oscillations. Their occurrence implies a series of extreme fluctuations in climate in the Northern Hemisphere, with beginnings and terminations occurring on short enough timescales to be relevant to people. The events highlight the sensitivity and rapid response of Earth climate to natural forcings, even if the causes are not yet fully understood. Glaciers in the subtropics and tropics are shrinking so fast that previously collected and archived ice cores may be the only direct record we have of them before the end of this century. Of particular note is the Kilimanjaro ice cap, which will likely disappear in the next decade (Thompson et al., 2002).

Analysis of trapped air bubbles in Greenland and Antarctic ice cores also has provided valuable insights into fluctuations in atmos-

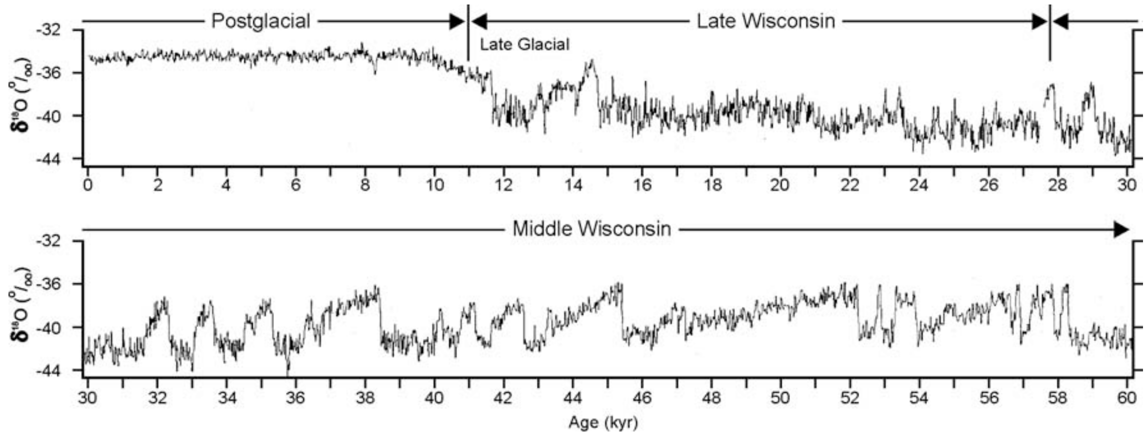

Figure 1 $\delta^{18}O$ record from GISP2 ice core, Greenland, for the 54 ^{14}C ka (modified from Stuiver and Grootes, 2000, their Figure 1). The large and rapid changes in Northern Hemisphere climate during the late Pleistocene were driven by natural processes.

pheric carbon dioxide and methane over the past 800,000 years. The data have confirmed a lock-step relation between concentrations of these gases and climate (Petit et al., 1999), although what is driving what continues to be debated.

Fluctuations in isotope and gas concentrations in the Holocene parts of ice cores were initially overshadowed by the much larger swings of the Pleistocene. Recently, however, scientists have come to understand that Holocene climate has been far from benign - it has fluctuated sharply and significantly on timescales ranging from decades to millennia. The ice-core records are complemented by annually resolved reconstructions of Holocene climate provided by measurements of tree-ring widths (Mann et al., 1999). The proxy record of climate provided by old trees and instrumental climate data have elucidated the complex climate pattern of the past millennium, a period popularized by the term "Little Ice Age" (Figure 2). It is clear from the proxy record that climate fluctuated due to natural causes prior to the beginning of the Industrial Revolution, due perhaps to changes in volcanism or solar irradiation. Researchers, however, have pointed out that the warming of the past several decades is highly unusual and cannot be explained by natural forcing. They argue that the accelerating rise in atmospheric greenhouse gases has become a more important driver of climate change than natural ones.

An additional point of note in the intense research effort on past climates being made by Quaternary scientists is that it is inherently interdisciplinary. Like all large, societal issues, climate research is difficult and complex. It requires scientists able and willing to operate as teams, commonly comprising geologists, oceanographers, glaciologists, geographers, biologists, chemists, and many others. Quaternary scientists are perfectly positioned through their training and inclination to operate within such a framework.

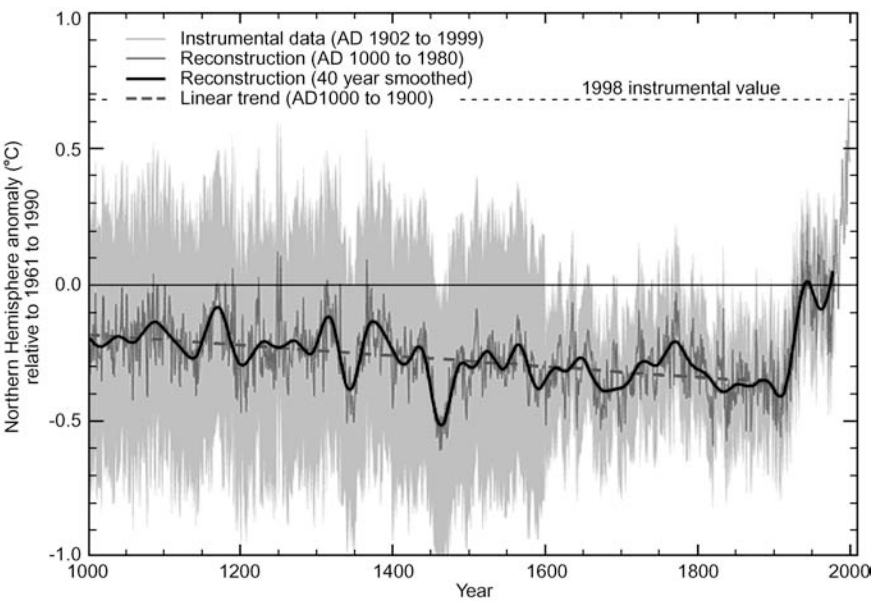

Figure 2 Millennial Northern Hemisphere temperature reconstruction based on tree-ring data (blue) and instrumental data (red) from AD 1000 to 1999 (adapted from Mann et al., 1999). Smoother version of the Northern Hemisphere series (black), linear trend from AD 1000 to 1850 (purple-dashed) and two standard error limits (grey shaded) are shown.

Natural hazards

Earth is a dangerous place. Disasters resulting from "normal" Earth processes typically claim tens of thousands of lives every year and cause hundreds of billions of dollars damage to human works. Clearly, society has an interest in reducing this terrible toll. Much of what needs to be done to reduce risk from earthquakes, tsunami, landslides, volcanic eruptions, floods, severe storms, and other disasters lies outside earth science, within the domains of civil engineering and the social sciences. But earth scientists also have a role to play. Specifically, they are key to improving our understanding of the physical processes responsible for natural disasters and for providing reliable data on the frequency and magnitude of past events. In most parts of the world, instrumental and written records of past natural disasters are much too short to provide adequate data for the frequency-magnitude relations that are required to confidently forecast future disasters. Quaternary stratigraphy and landforms provide a wealth of information on most hazardous natural events In this section, I provide one example of the contribution Quaternary scientists are making to improving knowledge of a specific natural hazard–large earthquakes on the west coast of North America, notably in two areas—the Pacific Northwest and California.

Prior to the 1980s, our understanding of earthquake risk on the west coast of North America was based almost entirely on instrumental data that date back only to the late nineteenth century. Although clearly important, the instrumental record alone may provide a biased view of both hazards and risk.

Beginning with seminal work of Atwater (1987, 1992), geologists provided unequivocal lithostratigraphic and biostratigraphic evidence

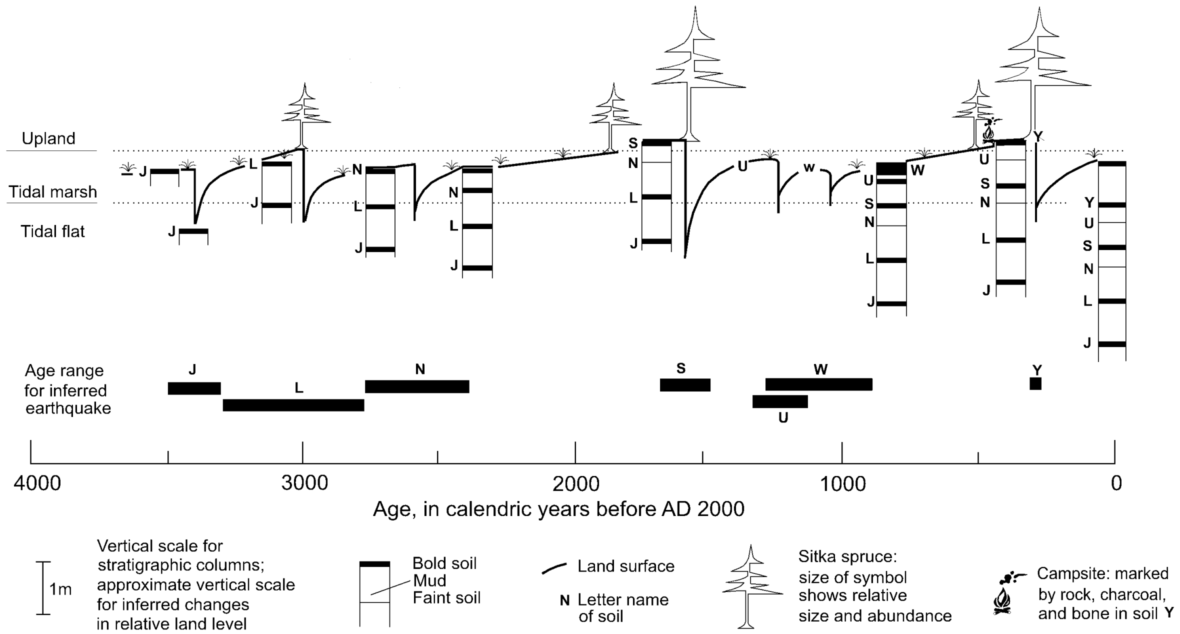

Figure 3 Effects of great earthquakes on tidal marsh stratigraphy over the past 4000 years in southern coastal Washington (adapted from Atwater and Hemphill-Haley, 1997). The earthquakes correspond to times of abrupt land-level change, when marshes dropped lower in the intertidal zone. The horizontal bars indicate the intervals in which the earthquakes occurred (95% confidence interval) and are based on radiocarbon ages. Only the last of the seven earthquakes is precisely dated; it occurred on January 26, 1700.

for historically unprecedented, recurrent great (M>8) earthquakes and accompanying tsunamis at the Cascadia subduction zone, which extends along the Pacific coast from northern California to southern British Columbia (Atwater et al., 1995, Clague, 1997). The evidence includes distinctive couplets of thin marsh peat overlain abruptly by thicker tidal mud; layers of tsunami sand commonly separate these two lithologies. Plant macrofossils, diatoms, and foraminifera reveal up to 2 m of sudden land-level change at the peat-mud contacts, consistent with coseismic subsidence. Radiocarbon dating of fossil plants in growth position at the peat-mud contacts has provided a chronology of great subduction zone earthquakes extending back almost 4000 years (Figure 3). Study of tsunami sand layers in tidal marshes and low-lying coastal lakes has provided important insights into the size of tsunami triggered by Cascadia subduction zone earthquakes (Clague and Bobrowsky, 1994, Kelsey et al., 2005). These geologic studies have been complemented by geodetic and geophysical research that has provided new insights into strain accumulation along the subduction zone.

Through LIDAR (Light Detection and Ranging) surveys, trench investigations, and other studies, geologists also identified crustal faults in populated areas of the Puget Lowland of Washington State that slipped during large earthquakes in the Holocene, but not historically (Nelson et al., 2003, Karlin et al., 2004). Much similar work has been done to document the slip history of active faults in California, thus extending the instrumented record of seismicity and providing a much better basis for establishing future probabilities of earthquakes (Rubin et al., 1998, Dolan et al., 2000, Jing et al., 2006). The research combines geomorphic interpretation of fault traces with interpretation of offset Quaternary strata in trenches excavated along and across faults. The studies of Kerry Sieh and his students and colleagues (Sieh, 1984, Sieh et al., 1989) on offset strata in trenches across strands of the San Andreas fault in southern California stand out, because they were the catalyst for a huge effort by geologists to better understand earthquake risk in California, which in turn led to improvements in earthquake engineering and better public awareness of earthquakes. The contributions of geologists in extending earthquake histories, not only in western North America but in most other active orogens, have greatly improved understanding of seismic hazards and risk, and have more broadly elevated public awareness of earthquakes and their effects.

Concluding remarks

Earth has a 4.5 billion year history, of which the Quaternary Period is only 0.04 percent. Yet, the events of this brief interval are important to people. Our genus appeared during the Quaternary, and its evolution was strongly shaped by the large and abrupt changes in climate that caused the episodic growth and decay of Northern Hemisphere ice sheets. Quaternary sediments, glaciers, and landforms contain most of the proxy records of past climate and catastrophes that are relevant to us. Accordingly, Quaternary researchers are at the forefront of the scientific movement to provide information of value to the public and policy makers.

Acknowledgements

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References

Atwater, B. F., 1987, Evidence for Holocene earthquakes along the outer coast of Washington state: Science, v. 236, pp. 942–944.

Atwater, B. F., 1992, Geologic evidence for earthquakes during the past 2000 years along the Copalis River, southern coastal Washington: Journal of Coastal Research, v. 97, pp. 1901–1919.

Atwater, B. F., and Hemphill-Haley, E., 1997, Recurrence intervals for great earthquakes of the past 3500 years at northeastern Willapa Bay, Washington: U.S. Geological Survey Professional Paper 1576.

Atwater, B. F. and 15 others, 1995, Summary of coastal geologic evidence for past great earthquakes at the Cascadia subduction zone: Earthquake Spectra, v. 11, pp. 1–18.

Broecker, W. S., and Denton, G. H.,1990, The role of ocean-atmosphere reorganisations in glacial cycles: Quaternary Science Reviews, v. 9, pp. 305–343.

Clague, J. J. 1997. Evidence for large earthquakes at the Cascadia subduction zone: Earthquake Spectra, v. 35: 439–460.

Clague, J. J., and Bobrowsky, P. T., 1994, Tsunami deposits beneath tidal marshes on Vancouver Island, British Columbia: Geological Society of American Bulletin, v. 106, pp. 1293–1303.

Dansgaard, W. S., and Tauber, H., 1969, Glacier oxygen 18 content and Pleistocene ocean temperatures: Science, v. 166, pp. 499–502.

Dansgaard, W. S., Clausen, S. J., Gundestrup, N., Hammer, C. U., Johnsen, S. F., Kristindottir, P. M., and Reeh, N., 1982, A new Greenland deep ice core: Science, v. 218, pp.1273–1277.

Dolan, J. F., Sieh, K., and Rockwell, T. K., 2000, Late Quaternary activity and seismic potential of the Santa Monica fault system, Los Angeles, California: Geological Society of America Bulletin, v. 112, pp. 1559–1581.

Emiliani, C., 1955, Pleistocene temperatures: Journal of Geology, v. 63, pp. 538–575.

EPICA Community Members, 2004, Eight glacial cycles from an Antarctic ice core: Nature, v. 429, pp. 623–628.

Jing, L-Z., Klinger, Y., Sieh, K., Rubin, C., and Seitz, G., 2006, Serial ruptures of the San Andreas fault, Carrizo Plain, California, revealed by three-dimensional excavations: Journal of Geophysical Research, v. 111, 33 pp.

Johnsen, S. J., Dansgaard, W., Clausen, H. B., and Langway, C. C., Jr., 1972, Oxygen isotope profiles through the Antarctic and Greenland Ice Sheets: Nature, v. 235, pp. 429–434.

Karlin, R. E., Holmes, M., Abella, S. E. B., and Sylwester, R., 2004, Holocene landslides and a 3500-year record of Pacific Northwest earthquakes from sediments in Lake Washington: Geological Society of America Bulletin, v. 116, pp. 94–108.

Kelsey, K. M., Nelson, A. R., Hemphill-Haley, E., and Witter, R. C., 2005, Tsunami history of an Oregon coastal lake reveals a 4600 yr recorde of great earthquakes on the Cascadia subduction zone: Geological Society of America, v. 117, pp. 1009–1032.

Lorius, C. L., Merlivat, J., Jouzel, J., and Pourchet, M., 1979, A 30,000 year isotope climatic record from Antarctic ice: Nature, v. 80, pp. 644–648.

Mann, M. E., Bradley, R. S., and Hughes, M. K., 1999, Northern Hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations: Geophysical Research Letters, v. 26, pp. 759–762.

Nelson, A. R., Johnson, S. Y., Kelsey, H. M., Wells, R. E., Sherrod, B. L., Pezzopane, S. K., Bradley, L.-A., Koehler, R. D., III, and Bucknam, R. C., 2003: Geological Society of America Bulletin, v. 115, pp. 1388–1403.

Petit J. R. and 18 others, 1999, Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica: Nature, v. 399, pp. 429–436.

Rubin, C. M., Lindvall, S. C., and Rockwell, T. K., 1998, Evidence for large earthquakes in metropolitan Los Angeles: Science, v. 281, pp. 398–402.

Shackleton, N. J. 1967. Oxygen isotope analyses and Pleistocene temperatures reassessed: Nature, v. 215, pp. 15–17.

Shackleton, N.J. and Opdyke, N.D., 1973, Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28–238: Oxygen isotope temperatures and ice volumes on 105 and 106 year scale: Quaternary Research, v. 3, pp. 39–53.

Siegenthaler, U. and 10 others, 2005, Stable carbon cycle– climate relationship during the late Pleistocene: Science, v. 310, pp. 1313–1317.

Sieh, K., 1984, Lateral offsets and revised dates of large prehistoric earthquakes at Pallett Creek, Southern California: Journal of Geophysical Research, v. 89, pp. 7641–7670.

Sieh, K., Stuiver, M., and Brillinger, D., 1989, A more precise chronology of earthquakes produced by the San-Andreas Fault in southern-California: Journal of Geophysical Research, v. 94(B1), pp. 603–623.

Spahni, R. and 10 others, 2005, Atmospheric methane and nitrous oxide of the late Pleistocene from Antarctic ice cores: Science, v. 310, pp. 1317–1321.

Stuiver, M. and Grootes, P. M., 2000, GISP2 oxygen isotope ratios: Quaternary Research, v. 53, pp. 277–284.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Bolzan, J. F., Dai, J., Yao, T., Gundestrup, N., Wu, X., Klein, L., and Xie, Z., 1989, Holocene-Late Pleistocene climatic ice core records from Qinghai-Tibetan Plateau: Science, v. 246, pp. 474–477.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Lin, P.-N., Henderson, K. A., Cole-Dai, J., Bolzan, J. F., and Liu, K.-B., 1995, Late Glacial stage and Holocene tropical ice core records from Huascaran, Peru: Science, v. 269, pp. 46–50.

Thompson, L. G., Mosley-Thompson, E., Davis, M. E., Henderson, K. A., Brecher, H. H., Zagorodnov, V. S., Mashiotta, T. A., Lin, P.-N., Mikhalenko, V. N., Hardy, D. R., and Beer, J., 2002, Kilimanjaro ice core records: Evidence of Holocene climate change in tropical Africa: Science, v. 298, pp. 589–593.

Wells, A., and Goff, J., 2007, Coastal dunes in Westland, New Zealand, provide a record of paleoseismic activity on the Alpine Fault: Geology, v. 35, pp. 731–734.

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by Robin W. Dennell

Human migration and occupation of Eurasia

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The main current benefit of collaboration between Quaternary scientists and palaeoanthropologists (especially palaeolithic archaeologists) lies in providing a unique perspective on how human populations respond to long-term climate change. Eurasia has a superlative record of climatic changes over the last two million years, and an archaeological record that is regionally variable in quality, but which is drawn from a wide range of environmental and chronological contexts. At a continental scale, the integration of these records allows the past 2 Ma to be divided into six major themes of how hominins (our remote ancestors) and our own species responded to climatic changes at Milankovitch and sub-Milankovitch scales. These themes are the initial hominin colonisation of Asia after ~2 Ma; the dispersal of hominins into Europe in the Early Pleistocene and its eventual permanent colonisation in the Middle Pleistocene; the expansion of Acheulean, bifacial assemblages from the Levant to western Europe and India after 600 ka; the responses of hominin populations to Milankovitch-length climatic changes during the Middle Pleistocene; the expansion of modern humans after 100 ka across Eurasia and later into Australasia and the Americas; and the recolonisation at millennial scales of abandoned areas of Eurasia at the end of last ice age. As the quality of Quaternary and archaeological information improves, these responses of past human populations to climatic change will be documented at a level of detail unimaginable a few decades ago. Cumulatively, this type of collaboration provides a unique perspective on the consequences of large-scale climatic change upon human populations that is particularly relevant to current concerns of climate change

Introduction

The main theme of the last two million years of human prehistory in Eurasia is one of population movements resulting from climatic change. When conditions were favourable, humans (and their predecessors) dispersed into and often colonised new areas or re-colonised ones previously abandoned. As conditions deteriorated, the limits of human settlement contracted as populations retreated southwards; some areas were abandoned, and doubtless many populations became extinct. In Europe, the main climatic variables affecting hominin populations were winter temperatures and rain/snowfall: as ice sheets expanded and retreated, hominins followed suit and often most of northern Europe was abandoned. In Asia, where ice sheets were never as extensive, the main climatic variable determining where hominins could live was probably rainfall. This factor was particularly important in areas that are dependent upon rain from the Mediterranean, notably inland Southwest Asia and Central Asia; and also North China that lies at the northern limit of the East Asian summer monsoon. Figure 1 provides a useful summary model of the consequences of glacial and interglacial climates on hominin populations during the Pleistocene.

Pleistocene climatic changes in Eurasia are now known in great detail, thanks primarily to the marine isotope records of the North Atlantic, Mediterranean, Indian Ocean, South China Sea, and West Pacific. There are also some excellent terrestrial records from Asia (summarised in Dennell in press), notably the 22 Ma loess and palaeosol record of the Chinese Loess Plateau, a 10 Ma record from Lake Baikal in Siberia, and the 2.5 Ma loess and palaeosol record of Tajikistan, Central Asia. Other useful but partial terrestrial climatic sequences come from South China, India, the Arabian Peninsular and the Levant. The record of Pleistocene climate in the European peninsula is of course extremely well documented. As a result of these records, we can now begin to model and investigate human prehistory in Eurasia in terms of human responses to climatic shifts over Milankovitch cycles, as well as millennial and sub-millennial lengths. This signifies a major change (first developed in Europe in the 1980's; see e.g., Gamble, 1986) from using Pleistocene climatic sequences primarily as a means of dating fossils and stone tools to using them to model how hominin populations responded to different climatic and environmental conditions (see e.g., Roebroeks ,2001). With the information now available, palaeolithic archaeologists are uniquely equipped to study long term human responses to climate change.

Eurasian palaeoanthropology (including its Palaeolithic record) is largely about six major processes of migration into and colonisa-

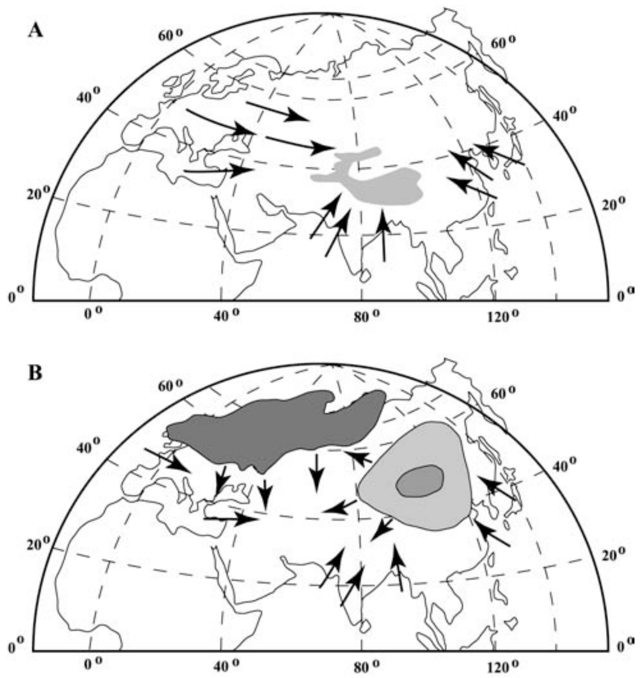

Figure 1 Dodonov and Baiguzina's model of Pleistocene glacial and interglacial climate.

tion of new areas, and their opposite conditions of abandonment and isolation. In favourable periods, the outcomes were the expansion of populations, the colonisation of new areas, and the integration of adjoining populations; in unfavourable (cold, arid) periods, the consequences were often the southward retreat of some populations, the abandonment of colonised areas, and the isolation or fragmentation of populations (see e.g., Dennell, 2007; Petraglia and Dennell, 2007). Consequently, many Eurasian regional Palaeolithic sequences show numerous discontinuities in their settlement records (Dennell 2003, 2004). For the most part, hominins danced to the rhythms of Pleistocene climatic change. However, their responses were not unchanging like those of other animals, because hominins evolved, and their behavioural capabilities developed. Hominins 0.5 Ma were undoubtedly more competent than their counterparts a million years earlier, and were even more competent at 35,000 ka and 15,000 ka. Thus conditions that might have been insurmountable for hominins at 500 ka were coped with 50 ka because of improvements in hunting, gathering and food-processing techniques, clothing, shelter, the use and control of fire, the ability of hominins to procure raw materials over great distances, improvements in their communication skills (especially language), as well as in their cognitive awareness of their social landscapes. Thus the Pleistocene hominin record of Eurasia can be seen as a game between the vicissitudes of Pleistocene climatic change on the one hand, and on the other, a hominin that gradually (or at times, suddenly) developed better means of coping with adverse climatic and environmental changes.

Six major processes of Pleistocene migration, dispersal and colonisation in Eurasia

The most important and fruitful interactions between Quaternary studies and palaeoanthropology continue to be in six areas of research—two each in the Early and Middle Pleistocene, and three in the Upper Pleistocene.

1) The expansion of hominins (particularly Homo) from Africa.

The earliest widely accepted evidence for hominins outside Africa is from Dmanisi, Georgia, where the remains of hominins and stone tools ca. 1.75 Ma have been found. These hominins were a short, small-brained and very primitive form of *Homo erectus*. Slightly younger evidence of *H. erectus* has been found in Java, ca. 1.6 Ma, and probably in the Nihewan Basin, North China, where the oldest stone tools are ca. 1.66 Ma, although so far associated hominin remains have not been found. Two major issues of ongoing debate are when hominins first dispersed out of Africa, and whether *H. erectus* was the first and only hominin to leave in the Late Pliocene. On current evidence, it is possible that *H. erectus* originated in Southwest Asia from a population that left Africa before 2 Ma, and then dispersed back into East Africa as well as eastwards to Java and China. Other related issues are how Early Pleistocene hominins responded to the "41 ka" world of minor glacial and interglacial episodes in continental Asia, and whether the few observations we have of Early Pleistocene hominins in Asia are derived from core areas of settlement (as is likely in the Levant, Georgia and Java), or areas that were inhabited only when conditions were favourable, as may have been the case in North China.

2) The earliest colonisation of Europe

The earliest incontrovertible and well-dated evidence for hominins in Europe is from Atapuerca, Spain, and is ca. 1.2 Ma. More abundant and slightly younger evidence ca. 1.0 Ma comes from the Orce Basin, Spain and Ceprano, Italy, and particularly from Atapuerca after 0.8 Ma. These hominins are probably descended from those at Dmanisi, and are usually classified as *H. antecessor*. These may have evolved into *H. heidelbergensis,* which is the main type of hominin evidenced in Europe after 600 ka. Ongoing research concerns are to model when and how often hominins dispersed westwards across southern Europe; when they first moved into northern Europe (where the earliest evidence is currently ca. 600 ka; see Parfitt et al., 2005); where the core populations were in MIS 16 (620–650 ka), MIS 14 (524–565) and MIS 12 (424–478 ka); and whether the hominin fossil and archaeological record from Europe indicates continual residence, or episodic dispersals and local extinctions.

3) The expansion of the Acheulean

The Acheulean bifacial hand axe is of the most distinctive and enduring features of the Early Palaeolithic record in Africa, Europe and Asia. The earliest examples are East African ca. 1.6 Ma, and the earliest in Eurasia are from 'Ubeidiya, Israel, ca. 1.4 Ma. They do not appear to have expanded out of the African and Jordan Rift Valley until after 800 ka. However, by ca. 500 ka, they are found 2,500 miles (4,000 km) to the east in India, and the same distance to the west in Europe. It remains uncertain whether the expansion of the Acheulean resulted from the migration of hominins, the diffusion of knowledge about the manufacture and use of a multi-purpose tool, or was part of the diffusion of a larger behavioural package that included the ability to hunt large animals and perhaps also control fire. It is also unclear whether the bulk of this expansion occurred in MIS 11 (362–423 ka), which appears from the Lake Baikal records to have been exceptionally long and mild in Central Asia (Prokopenko et al., 2002).

4) The mid-latitude, Middle Pleistocene record: colonisation and abandonment

The shift to the 100-ka world of the Middle Pleistocene after 600 ka (Mudelsee and Schultz 1997) had momentous consequences on hominin populations between 40–50ºN. Evidence across Eurasia from Britain (Stringer, 2006), Central Asia (Ranov and Dodonov, 1995) and North China (Zhou et al., 2000) all indicates that hominins abandoned these regions for up to 80% of the last 500–600 ka. This pattern is illustrated by the palaeoclimatic and Palaeolithic records from Tajikistan, Central Asia (Figure 2), which clearly shows that hominins were present only during interglacials. In Britain, the main reason why hominins retreated was because of the repeated advances of ice and low temperatures; in Central Asia and North China, reduced rainfall and harsher winters were probably the most important factors that led to the abandonment of these areas.

5) The early to mid-Upper Pleistocene: the expansion of modern humans (Out of Africa 2)

The main evidence for anatomically modern forms of *H. sapiens* dates from ca. 160–190 ka in East Africa, and ca. 130–125 ka in Southwest Asia. On current evidence, modern humans dispersed from East Africa (possibly following a coastal route; see e.g., Stringer, 2000) or the Levant after the last interglacial (MIS 5e) and colonised the Australian landmass ca. 55–60 ka, which they could only have done so by using boats with paddles or sails. Europe was colonised by modern humans much later, and probably between 35–30 ka. Here, the expansion of modern humans is intricately interwoven with the extinction of Neanderthals during MIS 3 (see e.g., Andel and Davies, 2003), and debate continues over the role of climatic instability, competition, and/or technological and cognitive differences between the two populations. In Asia, the expansion of modern humans across southern Asia was accompanied by an eastward expansion of Neanderthals across Central Asia in MIS 4 and 3 (Howell, 1999). The events and environmental circumstances that led to the extinction of the latter are unclear, as is the date of the last Asian Neanderthals.

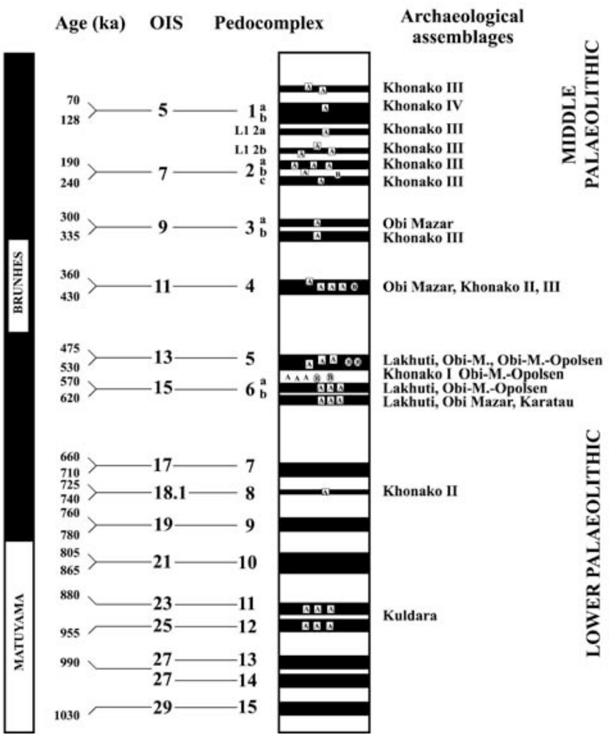

Figure 2 Age and stratigraphic context of Palaeolithic sites in Tajikistan. (Sources: Dodonov 2002; Tables 9 and 14; Ranov and Dodonov 2003; Figure 10). Black bars denote interglacial pedocomplexes (palaeosols); intervening white parts denote glacial loess. As is evident, this region was occupied only during interglacials.

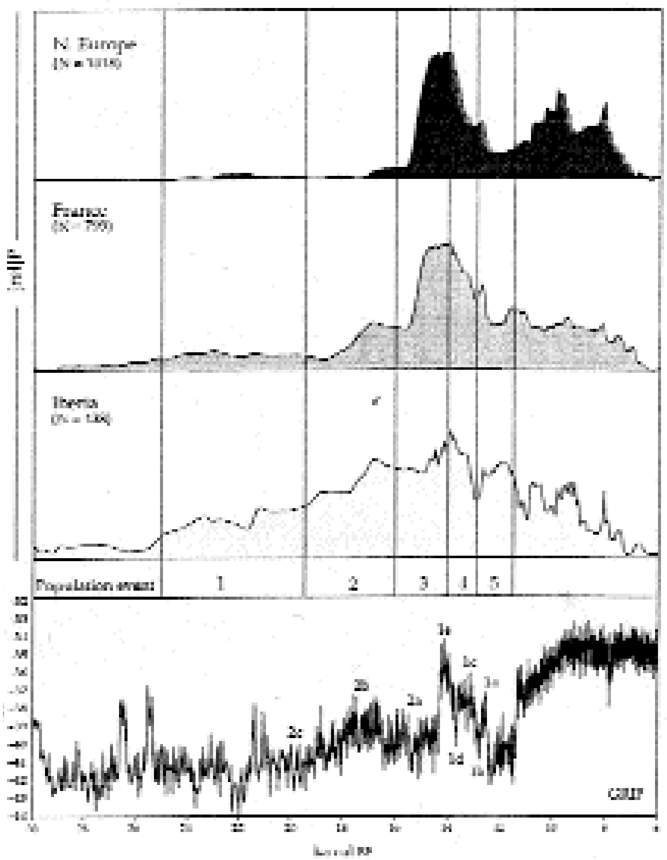

Figure 3 The late glacial recolonisation of N. Europe.

6) Late glacial expansion of human populations: colonisation and re-colonisation

Studies of a substantial part of the Eurasian late Palaeolithic after the last glacial maximum (ca. 21–15 ka) are primarily about the re-colonisation of areas previously too cold and/or ice-bound to inhabit. The re-colonisation of northern Europe is now documented in enormous detail (see Figure 3), and can be plotted with a resolution of only a few centuries. The re-colonisation of areas in Asia that were abandoned in the coldest parts of MIS 2 are known only sketchily, notably the Tibetan Plateau (first colonised 30–40 ka, almost certainly abandoned in MIS 2 and then re-colonised by 12 ka; see Madsen et al., 2001; Yuan et al., 2007) and Siberia. The latter area was first colonised in MIS 3, abandoned, and then swiftly re-colonised by groups that possessed the necessary clothing, hunting, fishing and trapping technologies, abilities to move across snow and endure extreme cold (Goebel, 1999). Some of these groups probably reached North America near the end of the Pleistocene across Beringia, the subcontinent now submerged by the Bering Straits (see e.g., Dalton, 2003); alternatively, some groups from western Europe may have reached the eastern coast of North America across the North Atlantic pack ice (see e.g., Bradley and Stanford, 2004).

Discussion

The combination of Quaternary and Palaeolithic research provides immense opportunities for obtaining a unique perspective on human responses to climate change over long-term timescales at a continental to regional scale. In some case—such as Middle Pleistocene Britain and Tajikistan—it is possible to model these in detail across glacial and interglacial cycles, and to show the climatic conditions that were conducive or intolerable for sustained human occupation. In exceptionally well-documented situations, such as the late glacial records of northern Europe, human responses to climatic changes over only a few centuries can be analysed. What we need are more well-dated archaeological and fossil hominins with climatic and environmental contexts, and more Quaternary data that can estimate variables such as rainfall, snowfall, and temperatures as with MIS 2, 3 and 5e, and perhaps 6 and 11.

References

Andel, T. van, and Davies, W., 2003, eds, Neanderthals and modern humans in the European landscape during the last glaciation: Cambridge, McDonald Institute Monograph.

Bradley, B., and Stanford, D., 2004, The north Atlantic ice-edge corridor: a possible Palaeolithic route to the New World: World Archaeology, v. 36, no. 4, pp. 459–478.

Dalton, R., 2003, The coast road: Nature, v. 422, pp. 10–12.

Dennell, R.W., 2003, Dispersal and colonisation, long and short chronologies: how continuous is the Early Pleistocene record for hominids outside East Africa?: Journal of Human Evolution, v. 45, pp. 421–440.

Dennell, R.W., 2004, Hominid dispersals and Asian biogeography during the Lower and Early Middle Pleistocene, ca. 2.0–0.5 Mya: Asian Perspectives, v. 43, no. 2, pp. 205–226.

Dennell, R.W., 2007, Archaeological Archives from Asia, 2.7 MYR – 300,000 years ago, in Elias, S.A., ed, Elsevier Encyclopedia of Quaternary Science: Elsevier B.V., pp. 73–89.

Dennell, R.W., in press, The Palaeolithic Settlement of Asia: Cambridge, Cambridge University Press.

Dodonov, A.E., 2002, Quaternary of Middle Asia: Stratigraphy, Correlation and Paleogeography: Moscow, Geos. (In Russian).

Dodonov, A.E., and Baiguzina, L.L., 1995, Loess stratigraphy of Central Asia: palaeoclimatic and palaeoenvironmental aspects: Quaternary Science Reviews, v. 14, pp. 707–720.

Gamble, C., 1986, The Palaeolithic Settlement of Europe: Cambridge, Cambridge University Press.

Gamble, C., Davies, W., Pettitt, P., Hazelwood, L., and Richards, M., 2005, The archaeological and genetic foundations of the European population

during the Late Glacial: implications for 'Agricultural Thinking': Cambridge Archaeological Journal, v. 15, pp. 193–223.
Goebel, T., 1999, Pleistocene human colonization of Siberia and peopling of the Americas: an ecological approach: Evolutionary Anthropology 1998, v. 6, pp. 208–227.
Howell, F.C., 1999, Paleo-demes, species clades, and extinctions in the Pleistocene hominin record: Journal of Anthropological Research, v. 55, pp. 191–243.
Madsen, D.B., Ma Haizhou, Brantingham, P.J., Gao Xing, Rhode, D., Zhang Haiying, and Olsen, J.W., 2006, The Late Upper Paleolithic occupation of the northern Tibetan Plateau margin: Journal of Archaeological Science, v. 33, pp. 1433–1444.
Mudelsee, M., and Schulz, M., 1997, The Mid-Pleistocene climate transition: onset of 100 ka cycle lags ice volume build-up by 280 ka: Earth and Planetary Science Letters, v. 151, pp. 117–123.
Parfitt, S.A., Barendregt, R.W., Breda, M., Candy, I., Collins, M.J., Coope, G.R., Durbridge, P., Field, M.H., Lee, J.R., Lister, A.M., Mutch, R., Penkman, K.E.H., Preece, R.C., Rose, J., Stringer, C.B., Symmons, R., Whittaker, J.E., Wymer, J.J., and Stuart, A.J., 2005, The earliest record of human activity in northern Europe: Nature, v. 438, pp. 1008–1012.
Petraglia, M.D., and Dennell, R.W., 2007, The Archaeology of Global Expansion 300,000–8000 years ago: Asia, in Elias, S.A., ed, Elsevier Encyclopedia of Quaternary Science: Elsevier, pp. 107–118.
Prokopenko, A.A., Williams, D.F., Kuzmin, M.I., Karabanov, E.B., Khursevich, G.K., and Peck, J.A., 2002, Muted climate variations in continental Siberia during the mid-Pleistocene epoch: Nature, v. 418, pp. 65–68.
Ranov, V.A., and Dodonov, A.E., 2003, Small instruments of the Lower Palaeolithic site Kuldara and their geoarchaeological meaning, in Burdukiewicz, J.M., and Ronen, A., eds, Lower palaeolithic small tools in Europe and Asia: British Archaeological Reports (International Series), v. 1115, pp. 133–147.
Roebroeks, W., 2001, Hominid behaviour and the earliest occupation of Europe: an exploration: Journal of Human Evolution, v. 41, pp. 437–461.
Stringer, C.B., 2000, Coasting out of Africa: Nature, v. 405, pp. 24–25.
Stringer, C.B., 2006, Homo Britannicus: the incredible story of human life in Britain: London, Penguin.
Yuan, Bao Yin, Huang Weiwen, and Zhang, D., 2007, New evidence for human occupation of the northern Tibetan Plateau, China during the Late Pleistocene: Chinese Science Bulletin, v. 52, no. 19, pp. 2675–2679.
Zhou, C., Liu, Z., Wang, Y., and Huang, Q., 2000, Climatic cycles investigated by sediment analysis in Peking Man's cave, Zhoukoudian, China: Journal of Archaeological Science, v. 27, pp. 101–109.

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by Jürgen Ehlers[1] and Philip Gibbard[2]

Extent and chronology of Quaternary glaciation

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In a recent INQUA project the extent of Pleistocene glaciations has been digitally mapped and the chronology of events reviewed. The onset of the present Ice Age in both hemispheres dates back to the Palaeogene. In Greenland, Iceland, North America and southernmost South America sizeable ice sheets formed well before 2.6 ka BP. In Alaska and on Tierra del Fuego the ice advanced further than in any later glaciations. Evidence for Early Pleistocene glaciation (2.6–0.78 Ma) has been reported from many parts of the world, but in most cases dating remains problematic, and the size of the glaciers and ice sheets is unknown. A number of Middle Pleistocene glaciations (0.78–0.13 Ma) have been identified, mostly correlated with MIS 16, 12 and 6, including the Donian, Elsterian and Saalian of Europe. The extent of the MIS 6 glaciations is well known. Especially in Eurasia the extent of the Late Pleistocene (0.13 Ma to present) glaciations had to be revised. Major ice advances are reported for 80–100 ka BP, c. 70–80 ka BP and c. 20 ka BP, with the earlier glaciations being most extensive in the east. The very different shapes of the ice sheets—Donian vs *Elsterian, Early* vs *Late Weichselian —are as yet difficult to explain and remain a challenge for climatic modellers.*

Introduction

The lecture by Louis Agassiz at the Naturforschende Gesellschaft in Neuchâtel on 24 July 1837 is generally regarded as marking the birth of glacial theory. Instead of talking about fish, which was thought to be Agassiz's field of expertise, he chose to explain the origin of the erratics by glacier transport. However, it took until 1863 before the glacial theory was generally accepted in Britain and North America. At that time neither the number of glaciations nor the age of the cold stages were known. Based on their meticulous observations in the Alps, Penck and Brückner (1901/1909) concluded that all the glacial landforms they had found could be traced back to four major Pleistocene glaciations (Günz, Mindel, Riss, Würm). This view was generally accepted, and Penck and Brückner's stratigraphical scheme was applied on a global scale. Only very gradually it became clear, that the Alpine stratigraphy was not the key to all glacial sequences, and that glaciation had set in much earlier than the pioneers of Quaternary research had suspected. More and ever older glacial deposits were identified in Iceland, South America, Antarctica and Greenland. It also turned out that the sea floor held a more complete record of Pleistocene climatic history than any terrestrial sequence. Recent investigations into the distribution of marine ice-rafted debris (IRD) have shown that Northern Hemisphere glaciation began as early as 44 million years ago (Triparti et al., 2008). Greater precision in the resolution of glacial sequences has being achieved over the last two decades thanks to innovations and refinements in numerical-dating techniques, in particular for the later Middle and Late Pleistocene and throughout the Holocene.

The onset of glaciation

The onset of the present Ice Age in both hemispheres dates back to the Palaeogene. In the Miocene, glaciation became established in various mountain areas, for example in Alaska and Iceland. In most cases the traces of those early glaciations are restricted to individual sites, and only very vague limits of glaciation can be drawn. Exceptions include the Great Patagonian Glaciation in southern South America (Coronato et al., 2004) and the early glaciations in the Nebraska-Iowa area of the USA. In Alaska and in northwestern Canada the ancient ice sheets are also known to have reached beyond the limits of all later glaciations and their extent has been well mapped (Barendregt and Duk-Rodkin, 2004).

Although it had started early, glaciation in the Southern Hemisphere has always been limited by the lack of available landmass. Apart from Antarctica, only southernmost South America reached sufficiently pole-wards to allow extensive early glaciation (Figure 1). On Tierra del Fuego early ice sheets extended to the shelf edge (Coronato et al., 2004).

In the northern hemisphere, from Iceland, the oldest tillites indicate that mountain-glaciation first occurred in the Miocene (Table 1), prior to 7–6 million years ago. Subsequently almost 30 glacial events are represented since that time. There is evidence to suggest a progressive growth of glaciers during the late Pliocene (Geirsdóttir, 2004).

The oldest hint of early glaciation in Scandinavia is ice-rafted debris (IRD) in the Norwegian Sea sediments, dating from the middle Miocene. It suggests that incipient glaciations occurred on adja-

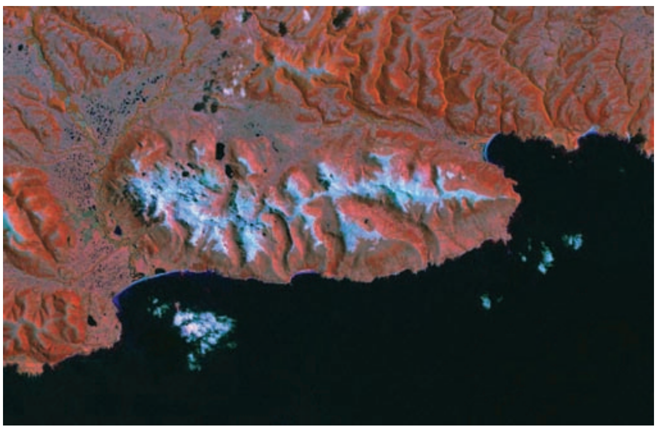

Figure 1 Landsat 7 ETM satellite image showing details of the glacial landscape in south-eastern Tierra del Fuego. (NASA Landsat Program, Landsat ETM+ scene p225r098_7p20020209_z19, USGS, Sioux Falls, of February 9th, 2002, Bands 4,7,3. Source: Global Land Cover Facility,* www.landcover.org*).

***Table 1** Occurrence of glaciation in Europe through the Cenozoic based on observations presented in contributions to the INQUA project ‚Extent and Chronology of Quaternary Glaciations' (Ehlers and Gibbard, 2004). Purple squares = glacial deposits; ? = possible glacial deposits; ~ = glaciomarine sediment; MIS = Marine Isotope Stage.*

Stage	Weichselian			Saalian		Elsterian	Cromerian			Early Pleistocene					Plio-/Pleistocene		Pliocene		Miocene	
Magnetostratigraphy	■	■	■	■	■	■	■	■	■ B	M			■		■	■ M	■ G			
MIS (approx.)	2	4	6	6	8	?12	?14	16	? 18 or 20	22+	34 - 38	60	64 - 72	?78 - 82	c.100 - 104					
Austria	■			■		■	■													
Belarus	■			■	■ ?	■	■													
Croatia	■		■	■		■														
Czechia	■			■		■														
Denmark	■		■	■		■	■ ?	■ ?	■											
Great Britain	■		■	■		■		■ ?												
Estonia	■		■	■		■														
Finland	■	■ ?	■	■		■ ?														
France (Massif Central)	■																			
North Germany	■		■ ?	■		■														
South Germany	■			■		■ ?				■					■	■				
Greece	■			■		■														
Iceland	■		■	■	■ ?	■ ?	■	■	■	■	■		■		■	■	■ ~	■ ~	■ ~	■ ~
Ireland	■		■ ?	■	■ ?	■ ?														
Italy	■		■	■	■ ?	■ ?	■	■		■	■ ?		■ ?		■ ?	■				
Latvia	■		■ ?	■		■ ?		?												
Lithuania	■			■	■ ?	■							■							
Netherlands				■		■	■				■									
Norway	■	■	■	■	■	■ ?		?		■	■		■ ?	■ ?	■ ? ~	■		■ ? ~		■ ? ~
Poland	■		■	■	■	■		■												
Russia (European Part)	■		■ ?	■		■	■	■ ?												
Siberian Lowlands	■	■	■	■		■														
Sweden	■	■	■	■	■ ?	■ ?														
Slovenia	■			■		■		■												
Spain	?		■			■ ?		■ ?												
Switzerland	■	■ ?	■	■		■	■	■	■		?		?		■	■	■			
Ukraine	■			■		■		■ ?												
Barents Sea	■	■ ?		■	■ ?	■ ?		■	■ ?	■	■		■ ?	■ ?	~		~	~	~	~
Kara Sea	■			■		■ ?														
North Atlantic	~		~			~							~	~	~		~	~	~	~
North Sea	■	■ ~	■	■		■		?			■									

cent land areas some 12–14 Ma ago (Thiede et al., 1998). The increased supply of IRD at approximately 3.2–2.7 Ma reflects a strengthening of northern hemisphere large-scale glaciations (Jansen and Sjøholm, 1991; Mangerud et al., 1996).

Early Pleistocene (2.6–0.78 Ma, MIS 103–MIS 19)

Evidence for Early Pleistocene glaciation (2.6–0.78 Ma) has been reported from many parts of the world, but in most cases dating remains problematic, and the size of the glaciers and ice sheets is unknown. In the southern hemisphere, glaciation in New Zealand began about 2.6 million years ago and in Tasmania at about 1 million years ago (Colhoun & Shulmeister, 2007). In the glacial maximum, the New Zealand glaciers covered about one third of the South Island (Suggate, 2004). Early Pleistocene glaciation was widespread in southern South America (Coronato et al., 2004). In Africa two Early Pleistocene glaciation phases are reported from Mount Kenya (Mahaney, 2004).

In North America Early Pleistocene glaciation is known from northern Canada (Horton Ice Cap), and there is also evidence for the existence of a Cordilleran Ice Sheet (Barendregt & DukRodkin, 2004). The old tills known from Kansas, Nebraska, Missouri and Iowa seem to be either older or younger (Jennings et al., 2007) (Table 2).

The most continuous record of the glacial/interglacial history of Scandinavia is probably found in the large submarine fans on the continental slope, located in front of troughs where fast-moving ice streams crossed the continental edge. However, so far no long cores have been obtained from these fans. The oldest identified and dated glacial deposit on the Norwegian shelf is the Fedje Till, that is assigned an age of about 1.1. Ma (= Marine Isotope Stage (MIS) 34–36; Sejrup et al., 2000). Also, in the Barents Sea region, initial glacial growth is reflected in a pronounced increase in the general sedimentation rate along the Svalbard margin from around 2.3–2.5 Ma. (Elverhøi et al., 1998, Vorren et al., 1998).

At what time the first ice sheets advanced beyond the limits of the Scandinavian peninsula, is still unclear. Deposits of Early Pleistocene glaciations have been reported from Denmark. At Harreskov (Jutland) early Middle Pleistocene interglacial deposits are underlain by a clay-rich diamicton, interpreted as till. The age of this oldest record of glaciation in Denmark is unknown. It might either date back to the Menapian Stage (? MIS 34–36) or, more likely, to an older part of the Cromerian Complex, i.e., ?MIS 22–19; Houmark-Nielsen, 1987; 2004). Beyond that there is only indirect evidence.

In the Netherlands the first fragments of Scandinavian rocks occur in the Harderwijk Formation, dating from almost 1.8 Ma. The Hattem Beds of the Menapian Stage (MIS 34–36: c. 1.2 Ma) are the oldest strata that carry major quantities of Scandinavian erratics from East Fennoscandian and central Swedish (Dalarna) source areas (Zandstra, 1983). They may be interpreted as evidence of a first major ice advance beyond the limits of the present Baltic Sea, but so far no undisputed till of that age has been found (Ehlers, 1996).

One of the key sections for the Pliocene-Pleistocene glacial and environmental events in Iceland is the Tjörnes sequence on the island's northern coast. There, in a 600 m thick sequence of interbedded lavas, tills, marine and terrestrial sediments, at least 14 glaciations have been recorded since 2.5–2.0 million years ago. This is probably the best preserved terrestrial record anywhere for Early and Middle Pleistocene glaciations in the North Atlantic region. The first full-scale glaciation of Iceland, with an ice sheet covering most of the island, dates back to 2.2–2.1 million years ago (Geirsdóttir, 2004).

The onset of glaciation in the Alps is still poorly understood. Part of Penck and Brückner's (1901/09) original Günz deposits are known to be reversely magnetised, and first exposure dates have yielded an age of c. 2.3 Ma (Häuselmann et al., 2007). Thus they must date back to the Matuyama Chron (i.e., pre–0.8 My). Early glaciations have also been reported from the French, Italian and Swiss parts of the mountains. However, in many cases, like with the northern Alpine Donau and Biber Stage deposits, much of the evidence is based on sediments not directly of glacial origin, and the number and extent of Early Pleistocene Alpine glaciations remain unknown.

The classical Alpine Quaternary sequence is largely a morphostratigraphy (Jerz, 1993). It is based upon the concept that the so-called 'glacial series' of landforms formed during any ice advance

Table 2 Occurrence of glaciation in North America through the Cenozoic based on observations presented in contributions to the INQUA project ‚Extent and Chronology of Quaternary Glaciations' (Ehlers and Gibbard, 2004). Purple squares = glacial deposits; ? = possible glacial deposits; ~ = glaciomarine sediment; MIS = Marine Isotope Stage.

Stage	Weichselian			Saalian		Elsterian	Cromerian			Early Pleistocene					Plio-/Pleistocene	Pliocene		Miocene	
Magnetostratigraphy									B	M					M	G			
MIS (approx.)	2	4	6	6	8	?12	?14	16	? 18 or 20	22+	34 - 38	60	64 - 72	?78 - 82	c.100 - 104				
N Canada and Alaska	~	~	~	~	~	~	~	~	~	~	~	~	~	~	~	~	? ~		~
Alberta			?			?													
British Columbia	~	?	~		?						?				?	?			
California											?			?					
Breat Basin							?	?											
Illinois						?		?											
Minnesota										?	?	?	?	?	?				
Montana & N Dakota		?				?					?								
New England			?																
New Brunswick		?		?															
New York			?																
Nova Scotia		?	?																
Ohio										~									
Ontario																			
Pennsylvania										?									
Québec				?															
Rocky Mountains		?		?										?					
Washington		?								?	?								
Wisconsin		?													? ~		? ~		? ~
Greenland	~	~	~	~	~	~	~	~	~		~	~	~	~	~	~			

consists of a sequence of tongue basins with drumlins, moraine belts and gravel spreads. In the northern foothills of the Alps comprehensive morphological sequences of this type were initially found for only three glaciations; for the fourth this evidence was produced much later through investigations in Upper Austria. From the Early Pleistocene, the Biber and Donau glaciations no such landform assemblages have been preserved. As long as it was believed that the Alpine region was only affected by four great glaciations, morphostratigraphy seemed adequate for the tasks. However, today litho- and biostratigraphical methods are increasingly used to update the Alpine Quaternary stratigraphy and palaeomagnetic investigations contribute to an improved dating of the sedimentary record.

Middle Pleistocene (0.78–0.13 Ma, MIS 19–MIS 6)

A number of Middle Pleistocene glaciations have been identified worldwide. In New Zealand, the Waimea and Waimaunga glaciations are correlated with MIS 6 and 8. The preceding Nemona glaciation is tentatively correlated with MIS 10 (Suggate, 2004). On Tasmania so far only the Middle Pleistocene Henty glaciation has been identified (Colhoun, 2004; Fitzsimons et al., 1990). In southern South America (Patagonia) three Middle Pleistocene glaciations are distinguished (Coronato et al., 2004). Middle Pleistocene glaciations are also known from the high mountains further to the north, e.g. Columbia (Helmens, 2004) and Ecuador (Heine, 2004). Also in Africa the high mountains such as Mount Kenya were glaciated in the Middle Pleistocene (Mahaney, 2004) (Table 3).

In Asia, Middle Pleistocene (MIS 6) glaciation has been reported from the northern Japanese Alps (Sawagaki et al., 2004). The high mountain ranges of Asia were glaciated in the Middle Pleistocene, and an ice cap seems to have existed at least on part of the Qinghai-Xizang (Tibetan) Plateau (Zhou et al., 2004).

In North America, after the collapse of the traditonal subdivision of the Pleistocene into Nebraskan, Kansan, Illinoian and Wisconsinan glaciations, many questions remain open with regard to the early Middle Pleistocene ice sheets. Apart from dating problems, there are difficulties with correlations over large distances. Therefore in some cases and the old glaciations have to be simply put together as 'pre-Illinoian' (Stiff and Hansel, 2004). Apart from fossil soils, magnetostratigraphy and dated volcanic ashes help to subdivide the glacial sequence. The 'classical Kansas' till (now Independence Formation) was found to have been deposited c. 600 to 700 ka BP. It represents the most extensive glaciation in central North America (Jennings et al., 2007). The extent of the Illinoian glaciation (MIS 6) is clear in all areas, where the ice sheet advanced beyond the limits of the subsequent Wisconsinan glaciation, which was the case in most areas along the southern ice margin.

The oldest continental European glaciation with a widespread till sheet is Middle Pleistocene. In southern Russia, the Don lobe moraine sediment was found to be overlain by interglacial sediments bearing a fauna of the Tiraspol (Cromerian) Complex and another 4–5 interglacial palaeosols. Accordingly, the Don Glaciation (Donian Stage) is presumably c. 0.5–0.6 ma old (post-dating the Brunhes/Matuyama boundary) and relates to MIS 16 (Arkhipov et al., 1986, Astakhov, 2004). So far it has only beeen securely identified in its type region. A possible equivalent event has been suggested in Eastern England (Lee et al., 2004), this is still disputed.

The oldest glacial event that has left behind till sheets throughout northern Europe is the Elsterian Glaciation (MIS 12). Especially in the Netherlands and in Northwest Germany its outer limit is not yet completely clear, because it was subsequently overridden by the Saalian ice sheet and much of the evidence has been destroyed. Also in Britain, the Anglian (Elsterian) tills are the first widespread unequivocal evidence of large-scale Pleistocene glaciation. The Anglian ice sheet overrode the contemporary valley of the River Thames in southern East Anglia and also advanced into its southern tributary valleys. In northeastern Norfolk ice from both Scandinavia and the British glaciation centres interacted during the Anglian Stage. The ice sheet terminated in a large ice-dammed lake in the southern North Sea Basin (Gibbard, 2007). Although up to five different Anglian till units can be distinguished in parts of East Anglia, no evidence of a major intervening ice-free period has so far been discovered (Ehlers et al., 1991).

The Saalian Glaciation (MIS 10(?)–MIS 6) began with a non-glacial cold phase of unknown but probably rather long duration. This was interrupted by several interstadials before the continental ice sheets invaded north Germany and the Netherlands. This first, maximum Saalian ice advance is correlated with the Odranian glaciation in Poland and the Dnieper glaciation in Russia and the Ukraine. In the west, it reached the Lower Rhine and left behind enormous pushed end moraines in the Netherlands (Koster, 2005; Busschers, 2008).

In Britain, contemporaneous glaciation was similar in its extent to that during the late Pleistocene (Devensian) glaciation. Deposits from this Wolstonian Stage glaciation occur in the southern English Midlands, south of Birmingham, and in Yorkshire, Lincolnshire and the Fenland Basin. Extent of ice lobes in the North Sea basin is poorly known, but it is highly probable that British and Continental ice were confluent for a period during this phase (Carr, 2004). Con-

Table 3 Occurrence of glaciation in the rest of the world through the Cenozoic based on observations presented in contributions to the INQUA project ‚Extent and Chronology of Quaternary Glaciations' (Ehlers and Gibbard, 2004). Purple squares = glacial deposits; ? = possible glacial deposits; ~ = glaciomarine sediment; MIS = Marine Isotope Stage.

Stage	Weichselian			Saalian		Elsterian	Cromerian			Early Pleistocene					Plio-/Pleistocene	Pliocene		Miocene		Palaeogene
Magnetostratigraphy									B	M					M	G				
MIS (approx.)	2	4	6	6	8	?12	?14	16	? 18 or 20	22+	34 - 38	60	64 - 72	?78 - 82	c.100 - 104					
Antarctica + S Ocean	~	~	~	~	~	~	~	~	~	~	~	~	~	~	~	~	~	~	~	~
Argentina																				
Patagonia																				
Bolivia																				
Chile																				
China - Tibet								?												
China - Tianshu								?							?					
Columbia										?										
East African Mountains																				
Equador					?	?														
Japan			?																	
Mexico		?	?			?														
New Zealand																				
Tasmania								?								?				

sequently a substantial ice-dammed lake again formed in the basin during this advance (Busschers, 2008).

The Samarovo glacial maximum of West Siberia is considered to be of Saalian age. However, considering the scarcity of geological information from this region, a pre-Holsteinian glaciation may well have been the most extensive in eastern Central Siberia. During the glacial maximum all northward flowing rivers were blocked, and drainage of Siberia from as far east as Lake Baikal was redirected via the Aral Sea and Caspian Sea into the Black Sea and Mediterranean, multiplying its freshwater supply. Immediately west of the Urals, the position of the ice limits is still controversial. The Saalian limit was probably positioned in the Volga-Pechora interfluve area (Ehlers et al., 2004a).

At the end of the Saalian glacial maximum the ice in Denmark and North Germany possibly melted back beyond the southern Baltic Sea coast. Later readvances in Denmark and North Germany are probably the equivalents of the Warthe (Warta) Substage. Also, the Moscow Till of Russia is the equivalent of the Polish Warta Glaciation. Towards the east, its outer limit converges with that of the Older Saalian (Dnieper) glaciation, and it may even have advanced beyond the Dnieper glacial limit.

In the Alps, the classical Günz comprises several glaciations. Part of what has been originally refererd as Günz is Early Pleistocene, part is Middle Pleistocene. Between the Günzian and the Mindelian a separate Haslach Glaciation has been postulated, based on the occurrence of distinct gravel units south of Ulm (Schreiner, 1997). However, the scarcity of early Middle Pleistocene deposits and the lack of age control make it difficult to revise this part of the classical Alpine stratigraphy. Even the stratigraphy of the Alpine Rissian cold Stage is still far from solved—at least in major parts of the glaciated area. Neither the precise extent of the glaciers, nor the number of ice advances or their age, can yet be determined with certainty (Fiebig and Preusser, 2003).

The Middle Pleistocene saw glaciations on many other high mountains, such as, for instance, in Greece (Hughes et al., 2007).

Late Pleistocene and Holocene (0.13 Ma to present, MIS 1–MIS 5)

In Australia and New Zealand the Last Glacial Maximum occurred towards the end of the Last Glaciation, shortly after 20,000 BP (MIS 2; Suggate, 2004; Colhoun, 2004). The same seems to be true for South America and the High Mountains of Africa (see various contributions in Ehlers and Gibbard, 2004c). In some regions, however, indications of earlier ice advances during the Last Glaciation have also been found, that might have occurred at MIS 5d or 4.

In North America the extent of Early and Middle Wisconsinan ice is not known. The best information is available for the Last Glacial Maximum, the Late Wisconsinan glaciation. It is now clear, that no ice-free corridor existed between the Cordilleran and the Laurentide Ice Sheet. Based on numerous radiocarbon dates, the North American deglaciation history has been mapped to great detail. The Laurentide Ice Sheet reached its maximum position at about 22 ka B.P., well in advance of the Cordilleran Ice Sheet. It took until 18 ka B.P. before the Wisconsinan ice sheets all over North America had reached their maximum (Dyke, 2004; Andrews and Dyke, 2007).

The extent of Pleistocene glaciation in Highland Asia is still a matter of debate. Kuhle's (1989) idea that the Tibetan Plateau was covered by a thick ice sheet has been refuted by other workers (Lehmkuhl and Owen, 2005). All authors agree that the Equilibrium-Line Altitudes in parts of Highland Asia were lowered by over 1000 m (Kuhle, 2004; Owen, 2007), and that glaciers were more extensive in the past, but how far this former glaciation reached is still a matter of debate. The interpretations rely heavily on the reliability of cosmogenic exposure dating.

In the 1970s through the widespread use of remote sensing data many push moraines were detected in the West Siberian and Pechora

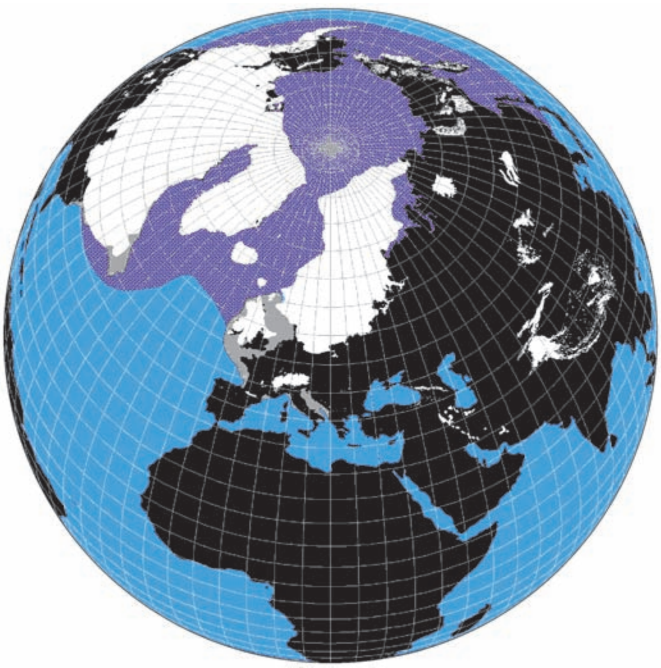

Figure 2 The maximum extent of the Northern Hemisphere LGM ice sheets (from Ehlers and Gibbard, 2004) and the approximate extent of over 0.5 months annual sea-ice cover at the LGM.

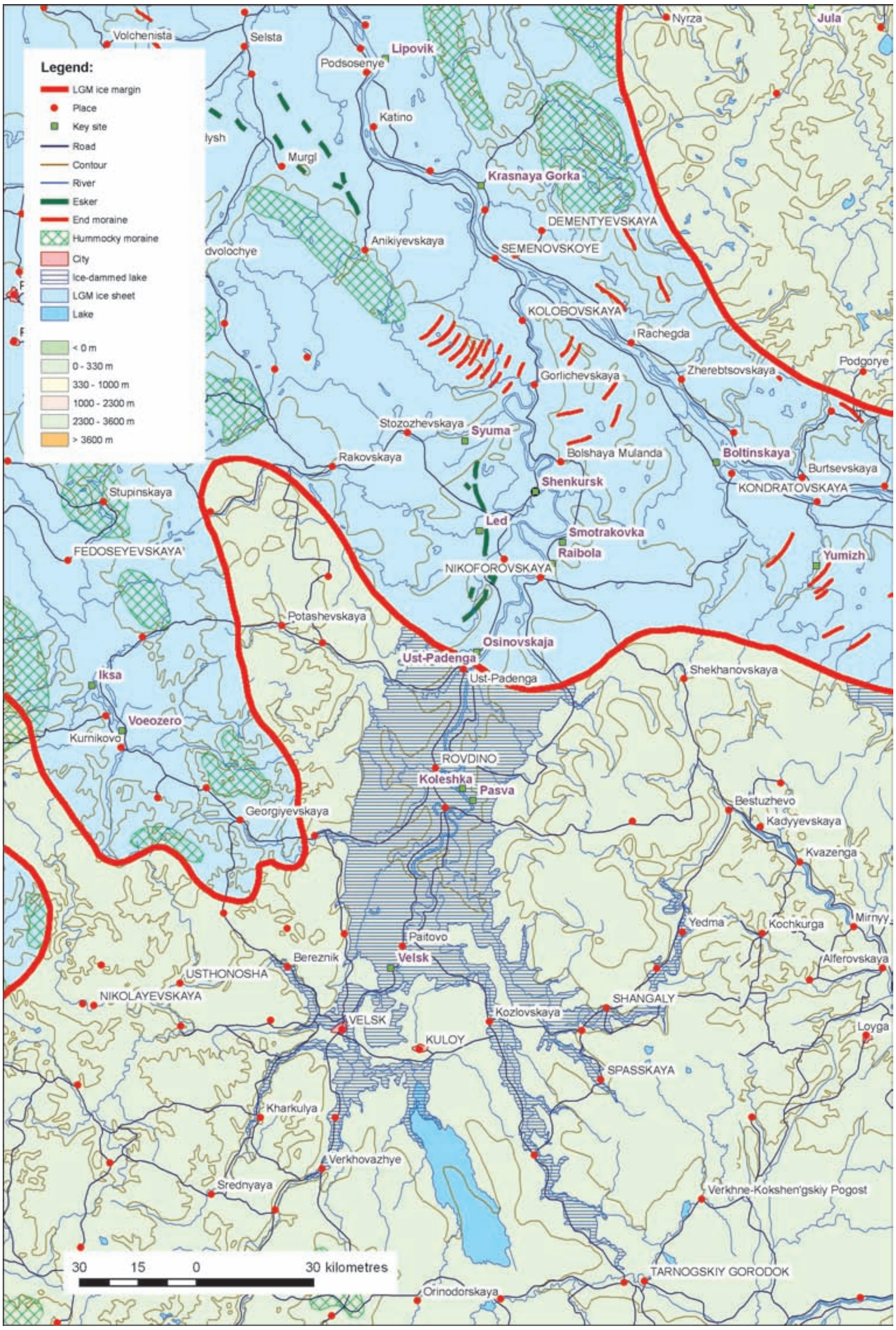

Figure 3 Extent of the Late Weichselian ice sheet in northwestern Russia. The extent of the ice lobes is controlled by the topography. Northward-flowing rivers are dammed by the ice sheet. The key sites refer to Eemian terrestrial deposits, either covered or not covered by Late Weichselian till. Excerpt from Map QL31 from Ehlers and Gibbard, 2004.

Lowlands, the configuration of which in most places contradicted the old mountain glaciation hypothesis. Obviously, a shelf-centered ice sheet had advanced onto the coastal lowlands. Northbound drainage was blocked by the advancing glaciers, forming huge ice dammed lakes. Apart from ice marginal features belonging to the vast Kara ice sheet, only traces of small alpine glaciers were found in the Polar Urals.

The first major glacial advance from the Barents and Kara seas onto the Russian mainland occurred during an early part of the Weichselian Stage, some 80–100 ka years ago. During this glaciation a huge ice dammed lake, Lake Komi, formed over the Pechora Lowland in the European part of northern Russia. Probably an even larger ice-dammed lake existed in the West Siberian Lowland. The last ice advance that reached the mainland culminated soon after 60 ka and deposited the Markhida moraine, north of the Arctic Circle in the Pechora drainage basin (Svendsen et al., 2004). The assumption that the Late Weichselian ice sheet was much smaller than the penultimate glaciations was substantiated by radiocarbon dates obtained from frozen mammoth carcasses demonstrating that these northern areas were not covered by glacier ice more than 35 thousand years ago (Mangerud et al., 2002; Svendsen et al., 2004).

A major ice sheet did exist in the Barents Sea–Svalbard region at this time. However, this ice sheet did not expand onto the Russian mainland (Figure 2). Its limit was found well offshore in the Barents Sea (Mangerud et al., 2002).

The Putorana Plateau is the only part of the Russian mainland to the east of the White Sea where a sizeable ice sheet may have formed during the Late Weichselian. Several finite radiocarbon ages were obtained from beneath the inner circle of well-pronounced end morainic arcs that are ascribed to the Norilsk Stage. These moraines were deposited by outlet glaciers from an ice cap covering the mountain plateau. However, more recent investigations of the bottom sediments of Lake Lama, situated on the proximal side of the Norilsk Moraine, suggest that the lacustrine sedimentation in this basin began before the LGM. If correct, this may imply that the last coherent ice cap on the Putorna Plateau may be older than the Late Weichselian glaciation (Svendsen et al., 2004). Much new and detailed information is also available about the extent of the Scandinavian ice-sheet into Russia during the LGM (Figure 3).

The maximum ice advances of the last cold stage both in Britain and continental Europe did not occur before the last part of the Weichselian (Devensian) Stage. Nevertheless, there can be no doubt that extensive glaciers also existed in northern Europe during the Early and Middle Weichselian substages. The exact extent of those glaciations in Scandinavia, the deposits of which have been identified in Norway, Finland, and northern and central Sweden, is so far unknown. For the Middle Weichselian glaciation investigations from Finland (Salonen et al., 2008) suggest a more northeasterly dispersal centre than in the Late Weichselian glaciation (Figure 4).

According to current knowledge, the Late Weichselian glaciation of the Scandinavian Ice Sheet started around 28,000 BP. and

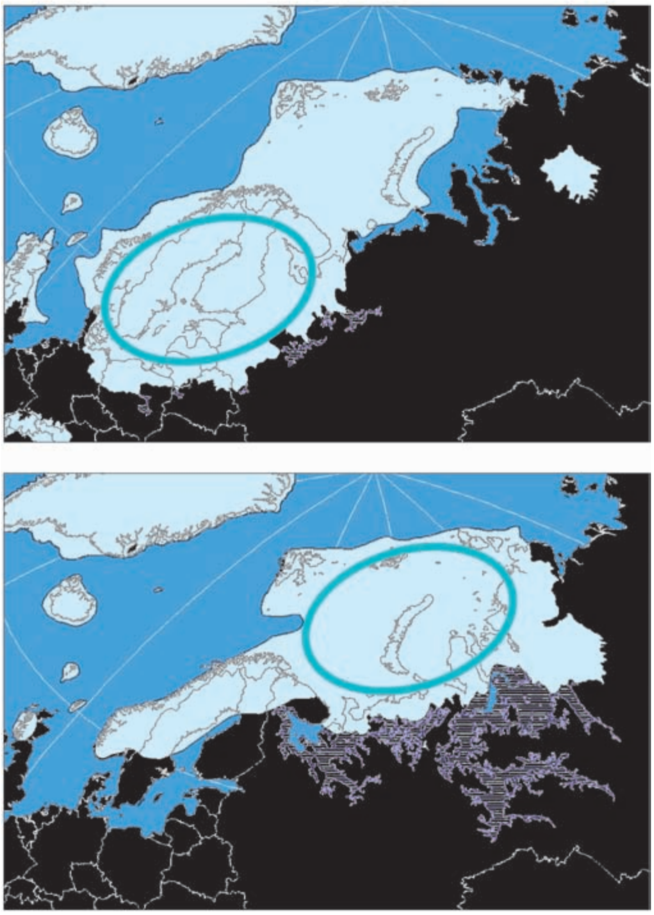

Figure 4 Comparison of the centres of the Early and Late Weichselian ice sheets. The Early Weichselian glaciation centre was positioned about 58°E / 75°N, whilst the Late Weichselian glaciation centre was at about 20°E / 62°N.

reached its culmination at about 22,000–18,000 BP. Radiocarbon ages from Poland suggest that it saw a very rapid, surge-like advance. The Lower Vistula region of Poland is the type region of the Vistulian (Weichselian) Glaciation (Ehlers et al., 1995). Five Vistulian till units have been identified, overlying Eemian marine deposits (MIS 5). The maximum extent of the Late Weichselian ice sheet south of the Baltic Sea is rather well mapped. The Weichselian ice did not cross the Elbe River. Three Late Weichselian ice advances can be distinguished in northeast Germany. The maximum Brandenburg Advance is assumed to have taken place at about 18,000 BP. but no precise dates are available. The Pomeranian Advance is older than 13,500 BP., whilst the Mecklenburg Advance, which is equivalent to the Fehmarn Advance of Schleswig-Holstein, is assigned to the period 13,200–13,000 BP. It thus coincides with the Oldest Dryas Chronozone (Ehlers, 1996).

During the Weichselian glacial maximum, the Baltic Sea depression did not control ice-movement directions, but the ice flowed radially from the centre to the margins. During the later Pomeranian Phase, however, ice flow was strongly controlled by the shape of the Baltic Sea depression. During this phase a Baltic ice stream advanced from the south onto the Danish Islands (Kristensen et al., 2000).

In both, Britain and Ireland, the main Devensian glaciation occurred in the later part of the cold stage (MIS 2). In Britain the Late Devensian glaciation is referred to as the Dimlington Stadial. Its glaciers advanced far south along the east coast of Britain, touching the northern coast of Norfolk. In the North Sea, the Dogger Bank remained ice-free, but major parts of the central and northern North Sea were glaciated (Kristensen et al., 2007). In the Irish Sea, ice advanced far to the south, touching the south Wales coast and possibly reaching as far as the Isles of Scilly. However, many details of the glacial history are still far from clear. Not only are there problems of connecting the British and Irish stratigraphic sequences with those of continental Europe, but also with one another. The last glaciation of Ireland, the Midlandian or Fenitian Glaciation, consisted of a major Irish Ice Sheet, and a smaller Kerry/Cork Ice Sheet in the southwest. The distribution of periglacial features suggests that a corridor more than 50 km wide between the two Irish ice sheets remained unglaciated (Knight et al., 2004).

In the Alps, a marked asymmetry is observed between glaciation of the northern and southern slopes. On the southern side of the Alps the equilibrium line altitude (ELA) is about 200 m higher than in the north. This contrast is further enhanced by the different altitudes of the two Alpine forelands (about 500 m in the north as opposed to about 100 m in the south). As a consequence, Quaternary glaciers have advanced far into the northern foreland of the Alps, whereas in Italy they terminated as soon as they had reached the foot of the mountains.

Initially a single undivided Würmian Glaciation was envisaged, subdivided only by a series of recessional end moraines. However, today it is quite clear that the Alps, like northern Europe and North America, experienced a Mid-Würmian and possible an Early Würmian ice advance. Only their extent is still a matter of debate (Preusser, 2004; Preusser et al., 2007).

Many of the Asian mountain ranges, such as the Werkhoyansk Mountains, the Jablonovyi or the mountains of Kamchatka have not yet been mapped in any detail. There are other formerly glaciated areas, such as the Pyrenees, the Carpathians, the Kaukasus, or the high mountains of Italy, Greece, Turkey, Iran and the Balkans which provide interesting information on former glaciation levels and equilibrium line altitudes. Comparison of the available maps with satellite imagery or a Digital Elevation Model makes it immediately clear, that much more work is needed in those areas. Remote sensing provides excellent tools to start such investigations, with imagery up to a scale of over 1:5,000 available through the QuickBird and Ikonos satellites. However, apart from all the technical progress, the decisive work to answer the open questions will still need to be done in the field.

Post-LGM ice front positions during the Late-glacial (13–10,000 ^{14}C yr BP; Hoek, this volume) and throughout the Holocene are known in great accuracy in many glaciated areas thanks to their excellent preservation and to chronological control, especially radiocarbon dating. Of particular significance is the 1,000 yr-long climatic deterioration in the Younger Dryas Chronozone (11,000 and 10,000 ^{14}C yr BP; Hoek, this volume) during which ice-front stillstand and local readvances have been mapped throughout the Northern Hemisphere glaciated regions (e.g., Andrews & Dyke, 2007; Svendsen et al., 2004). In the Southern Hemisphere, it is not yet certain whether there is evidence of the Younger Dryas cooling. For example, age control on the Late-glacial Waiho Loop and Misery Moraines in the Southern Alps of New Zealand relies on 10Be exposure dating. Ivy-Ochs et al., (1999) regard the moraines as equivalents of the Northern Hemisphere Younger Dryas Stadial, whereas Shulmeister et al., (2005) disagree. Denton et al., (1999) envision a Younger Dryas cooling for southern Chile, but again the dating is not very reliable.

References

Andrews, J. T., and Dyke, A. S., 2007, Late Quaternary in North America, *in* Elias, S. A., ed., Encyclopedia of Quaternary Science, v. 2: Amsterdam, Elsevier, pp, 1095–1101.

Arkhipov, S. A., Isayeva, L. L., Bespaly, V. G., and Glushkova, O., 1986, Glaciation of Siberia and North-East USSR: Quaternary Science Reviews, v. 5, no. 1–4, pp. 463–474.

Astakhov V., 2004, Middle Pleistocene glaciations of the Russian North: Quaternary Science Reviews, v. 23, no 11–13, pp. 1285–1311.

Barendregt, R. W., and Duk-Rodkin, A., 2004, Chronology and extent of Late Cenozoic ice sheets in North America: A magnetostratigraphic assessment, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations –

Extent and Chronology, Part II: North America, Developments in Quaternary Science, v. 2b: Amsterdam, Elsevier, pp. 1–7.
Busschers, F., 2008, Unravelling the Rhine. PhD thesis, Vrije Universiteit Amsterdam.
Colhoun, E., and Shulmeister, J., 2007, Late Pleistocene of the SW Pacific Region, *in* Elias, S. A., ed., Encyclopedia of Quaternary Science, v. 2: Amsterdam, Elsevier, 1066–1076.
Coronato, A.,, Martínez, O., and Jorge Rabassa, J., 2004, Glaciations in Argentine Patagonia, southern South America, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations–Extent and Chronology, Part III: South America, Asia, Africa, Australasia, Antarctica: Amsterdam, Developments in Quaternary Science, v. 2c: Elsevier, pp. 49–67.
Denton, G. H., Heusser, C. J., Lowell, T. V., Moreno, P. I., Andersen, B. G., Heusser, L. E., Schlüchter, C., and Marchant, D. R., 1999: Interhemispheric linkage of palaeoclimate during the last glaciation: Geografiska Annaler, v. 81 A, pp. 107–153.
Dyke, A. S., 2004, An outline of North American deglaciation with emphasis on central and northern Canada, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations–Extent and Chronology, Part II, Developments in Quaternary Science, v. 2b: North America: Amsterdam, Elsevier, pp. 373–424.
Ehlers, J., 1996, Quaternary and Glacial Geology: Chichester, Wiley.
Ehlers, J., and Gibbard, P. L. (editors) 2004a, Quaternary Glaciations – Extent and Chronology, Part I: Europe. Developments in Quaternary Science, v. 2a: Amsterdam, Elsevier.
Ehlers, J., and Gibbard, P. L. (editors) 2004b, Quaternary Glaciations – Extent and Chronology, Part II: North America. Developments in Quaternary Science, v. 2b: Amsterdam, Elsevier.
Ehlers, J., and Gibbard, P. L. (editors) 2004c, Quaternary Glaciations – Extent and Chronology, Part III: South America, Asia, Africa, Australasia, Antarctica. Developments in Quaternary Science, v. 2c: Amsterdam, Elsevier.
Ehlers, J., Astakhov, V., Gibbard, P. L., Mangerud, J., and Svendsen, J. I., 2007, Mid-Quaternary in Eurasia, *in* Elias, S. A., ed., Encyclopedia of Quaternary Science, v. 2, pp. 1036–1043.
Ehlers, J., Gibbard, P., and Rose, J. (eds) 1991, Glacial Deposits in Great Britain and Ireland: Rotterdam, Balkema.
Ehlers, J., Kozarski, S., and Gibbard, P. L. (eds) 1995, Glacial Deposits in North-East Europe: Rotterdam, Balkema.
Elias, S. A. (ed.), 2007, Encyclopedia of Quaternary Science, 4 vols: Amsterdam, Elsevier.
Elverhøi, A., Hook, R. L. B., and Solheim, A., 1998, Late Cenozoic Erosion and Sediment Yield from the Svalbard-Barents Sea Region: Implications for Understanding Erosion of Glacierized Basins: Quaternary Research, v. 44, pp. 209–241.
Fiebig, M., and Preusser, F., 2003, Das Alter fluvialer Ablagerungen aus der Region Ingolstadt (Bayern) und ihre Bedeutung für die Eiszeitenchronologie des Alpenvorlandes: Zeitschrift für Geomorphologie - Neue Folge, v. 47, pp. 449–467.
Fitzsimons, S. J., Colhoun, E. A., and Van De Geer, G., 1990, Middle Pleistocene glacial stratigraphy at Baxter Rivulet, western Tasmania, Australia: Journal of Quaternary Science, v. 5, pp. 17–27.
Geirsdóttir, Á., 2004. Extent and chronology of Glaciations in Iceland; a brief overview of the glacial history, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations – Extent and Chronology, Part I: Europe, Developments in Quaternary Science, v. 2a: Amsterdam, Elsevier, pp. 175–182.
Geirsdóttir, Á., and Eiríksson, J., 1994, Growth of an intermittent ice sheet in Iceland during the Late Pliocene and Early Pleistocene: Quaternary Research, v. 42, pp. 115–130.
Gibbard, P., 2007, Europe cut adrift: Nature, v. 448, pp. 259–260.
Häuselmann, P., Fiebig, M., Kubik, P.W., and Adrian, H., 2007, A first attempt to date the original "Deckenschotter" of Penck and Brückner in Bavaria: Quaternary International, v. 164–165, pp. 33–42.
Heine, K., 2004, Late Quaternary glaciations of Ecuador, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations – Extent and Chronology, Part III: South America, Asia, Africa, Australasia, Antarctica, Developments in Quaternary Science, v. 2c: Amsterdam, Elsevier, pp. 165–169.
Helmens, K. F., 2004, The Quaternary glacial record of the Colombian Andes, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations – Extent and Chronology, Part III: South America, Asia, Africa, Australasia, Antarctica, Developments in Quaternary Science, v. 2c: Amsterdam, Elsevier, pp. 115–134.
Houmark-Nielsen, M., 1987, Pleistocene stratigraphy and glacial history of the central part of Denmark: Bulletin of the Geological Society of Denmark, v. 36, pp. 1–189.
Houmark-Nielsen, M., 2004, The Pleistocene of Denmark: a review of stratigraphy and glaciation history, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations – Extent and Chronology, Part I: Europe, Developments in Quaternary Science, v. 2a: Amsterdam, Elsevier, pp. 35–46.
Hughes, P. D., Woodward, J. C., and Gibbard, P. L., 2007. Middle Pleistocene cold stage climates in the Mediterranean: New evidence from the glacial record: Earth and Planetary Science Letters, v. 253, pp. 50–56.
Ivy-Ochs, S., Schlüchter, C., Kubik, P. W., and Denton, G. H., 1999: Moraine exposure dates imply synchronous Younger Dryas glacier advances in European Alps and in the Southern Alps of New Zealand: Geografiska Annaler, v. 81 A, pp. 313–323.
Jansen, E., and Sjøholm, J., 1991, Reconstruction of glaciation over the past 6 Ma based on Norwegian Sea records. Nature, v. 349, pp. 600–603.
Jennings, C. E., Aber, J. S., Balco, G., Barendregt, R., Bierman, P. R., Rovey II, C. W., Roy, M., and Mason, J. A., 2007, Mid-Quaternary in North America, *in* Elias, S. A., ed., Encyclopedia of Quaternary Science, v. 2, pp. 1044–1051.
Jerz, H., 1993, Das Eiszeitalter in Bayern – Erdgeschichte, Gesteine, Wasser, Boden. Geologie von Bayern, Bd. 2: Stuttgart, Schweizerbart.
Knight, J., Coxon, P., McCabe, A. M., and McCarron, S. G., 2004, Pleistocene Glaciations in Ireland, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations – Extent and Chronology, Part I: Europe, Developments in Quaternary Science, Vol. 2a: Amsterdam, Elsevier, pp. 183–191.
Koster, E. A. (ed.) 2005, The Physical Geography of Western Europe: Oxford, Oxford University Press.
Kristensen, P., Gibbard, P., Knudsen, K. L., and Ehlers, J., 2000, Last Interglacial stratigraphy at Ristinge Klint, South Denmark: Boreas, v. 29, pp. 103–116.
Kristensen, Th. B., Huuse, M., Piotrowski, J. A., and Clausen, O. R., 2007, A morphometric analysis of tunnel valleys in the eastern North Sea based on 3D seismic data: Journal of Quaternary Science, v. 22, pp. 801–815.
Kuhle, M., 1989, Die Inlandvereisung Tibets als Basis einer in der Globalstrahlungsgeometrie fußenden, reliefspezifischen Eiszeittheorie: Petermanns Geographische Mitteilungen, v. 133, no. 4, pp. 265–285.
Kuhle, M., 2004, The High Glacial (Last Ice Age and LGM) ice cover in High and Central Asia, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations – Extent and Chronology, Part III: South America, Asia, Africa, Australasia, Antarctica, Developments in Quaternary Science, v. 2c: Amsterdam, Elsevier, pp. 175–199.
Lee J. R., Rose J., Hamblin R. J. O, Moorlock B. S. P., 2004, Dating the earliest lowland glaciation of eastern England: a pre-MIS 12 early Middle Pleistocene Happisburgh glaciation: Quaternary Science Reviews, v. 23, pp. 1551–1566.
Lehmkuhl, F., and Owen, L. A., 2005, Late Quaternary glaciation of Tibet and the bordering mountains: a review: Boreas, v. 34, pp. 87–100.
Mahaney, W. C., 2004,Quaternary glacial chronology of Mount Kenya massif, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations – Extent and Chronology, Part III: South America, Asia, Africa, Australasia, Antarctica, Developments in Quaternary Science, v. 2c: Amsterdam, Elsevier, pp. 227–231.
Mangerud, J., Astakhov, V., and Svendsen, J.-I., 2002, The extent of the Barents-Kara Ice Sheet during the Last Glacial Maximum: Quaternary Science Reviews, v. 21, no. 1–3, pp. 111–119.
Mangerud, J., Jansen, E., and Landvik, J., 1996, Late Cenozoic history of the Scandinavian and Barents Sea ice sheets: Global and Planetary Change, v. 12, pp. 11–26.
Owen, L. A., 2007, Late Quaternary in Highland Asia, *in* Elias, S. A., ed., Encyclopedia of Quaternary Science, v. 2: Amsterdam, Elsevier, 1109–1116.
Pedersen, S. A. S., 2005, Structurtal analysis of the Rubjerg Knude Glaciotectonic Complex, Vendsyssel, northern Denmark: Geological Survey of Denmark and Greenland Bulletin, v. 8, 192 pp.
Penck, A. & Brückner, E., 1901/1909, Die Alpen im Eiszeitalter, 3 vols: Leipzig, Tauchnitz.
Salonen, V.-P., Kaakinen, A., Kultti, S., Miettinen, A., Eskola, K., and Lunkka, J.-P., 2008, Middle Weichselian glacial event in the central part of the Scandinavian Ice Sheet recorded in the Hitura pit, Ostrobothnia, Finland: Boreas, v. 37, pp. 38–54.
Sawagaki, T., Aoki, T., Hasegawa, H., Iwasaki, S., Iwata, S., and Hirakawa, K., 2004, Late Quaternary glaciations in Japan, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations – Extent and Chronology, Part III: South America, Asia, Africa, Australasia, Antarctica, Developments in Quaternary Science, v. 2c: Amsterdam, Elsevier, pp. 217–225.
Schreiner, A., 1997, Einführung in die Quartärgeologie, 2nd ed.: Stuttgart, Schweizerbart.
Shulmeister, J., Fink, D., and Augustinus, P. C., 2005: A cosmogenic nuclide chronology of the last glacial transition in North-West Nelson, North Westland, New Zealand: Quaternary Science Reviews, v. 24, pp. 2207–2227.

Sejrup, H.-P., Larsen, E., Landvik, J., King, E. L., Haflidason, H., and Nesje, A., 2000, Quaternary glaciations in southern Fennoscandia: evidence from southwestern Norway and the North Sea region: Quaternary Science Reviews, v. 19, pp. 667–685.
Stiff, B. J., and Hansel, A. K., 2004, Quaternary Glaciations in Illinois, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations – Extent and Chronology, Part II: North America, Developments in Quaternary Science, v. 2b: Amsterdam, Elsevier, pp. 71–82.
Suggate, R. P., 2004, South Island, New Zealand; ice advances and marine shorelines, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations – Extent and Chronology, Part III: South America, Asia, Africa, Australasia, Antarctica, Developments in Quaternary Science, v. 2c: Amsterdam, Elsevier, pp. 285–291.
Svendsen, J. I., Alexanderson, H., Astakhov , V. I., Demidov, I., Dowdeswell, J. A., Funder, S., Gataullin, V., Henriksen, M., Hjort. C., Houmark-Nielsen, M., Hubberten, H. W., Ingólfsson, Ó., Jakobsson, M., Kjær, K. H., Larsen, E., Lokrantz, H., Lunkka, J. P., Lyså, A., Mangerud, J., Matiouchkov, A., Murray, A., Möller, P., Niessen, F., Nikolskaya, O., Polyak, L., Saarnisto, M., Siegert, C., Siegert, M. J., Spielhagen, R. F., Stein, R., 2004, Late Quaternary ice sheet history of Northern Eurasia: Quaternary Science Reviews, v. 23, no. 11–13, pp. 1229–1271.
Syverson, K. M., and Colgan, P. M., 2004, The Quaternary of Wisconsin: a review of stratigraphy and glaciation history, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations – Extent and Chronology, Part II: North America, Developments in Quaternary Science, v. 2b: Amsterdam, Elsevier, pp. 295–311.
Thiede, J., Winkler, A., Wolf-Welling, T., Eldholm, O., Myhre, A. M., Braumann, K.-H., Henrich, R., and Stein, R., 1998, Late Cenozoic History of the Polar North Atlantic: Results from Ocean Drilling: Quaternary Science Reviews, v. 17, pp. 185–208.
Tripati, A., Eagle, R., Morton, A., Dowdeswell, J., Atkinson, K., Bahe, Y., Dawber, C., Khadun, E., Shaw, R., Shorttle, O., and Thanabalasundaram, L., 2008, Evidence for Northern Hemisphere glaciation back to 44 Ma from ice-rafted debris in the Greenland Sea: Earth and Planetary Science Letters, v. 265, pp. 112–122.
Vázquez-Selem, L., and Heine, K., 2004, Late Quaternary glaciation of México, in Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations – Extent and Chronology, Part III: South America, Asia, Africa, Australasia, Antarctica, Developments in Quaternary Science, v. 2c: Amsterdam, Elsevier, pp. 233–242.
Vorren. T. O., Laberg, J. S., Blaumme, F., Dowdeswell, J. A., Kenyon, N. H., Mienert, J., Rumohr, J., and Werner, F., 1998, The Norwegian-Greenland Sea Continental Margins: Morphology and Late Quaternary Sedimentary Processes and Environment: Quaternary Science Reviews, v. 17, pp. 273–202.
Zandstra, J. G., 1983, Fine gravel, heavy mineral and grain-size analyses of Pleistocene, mainly glacigenic deposits in the Netherlands, *in* Ehlers, J., ed., Glacial Deposits in North-West Europe: Rotterdam, Balkema, pp. 361–377.
Zhou, S. Z., Jujun, L., Zhang, S. Q., Zhao, J.D., and Cui, J.X., 2004, Quaternary glaciations in China, *in* Ehlers, J., and Gibbard, P. L., eds, Quaternary Glaciations – Extent and Chronology, Part III: South America, Asia, Africa, Australasia, Antarctica, Developments in Quaternary Science, v. 2c: Amsterdam, Elsevier, pp. 105–113.

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by Eric W. Wolff

The past 800 ka viewed through Antarctic ice cores

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The later parts of the Quaternary are of particular importance for assessing our ability to understand the future operation of the Earth because the main boundary conditions are similar to those of today, and because we have a density of data that allows hypotheses to be tested rigorously. An important source of such data is Antarctic ice cores, now extending back 800 ka, and containing signals both of climate, and of climate forcing factors. The Antarctic ice core deuterium record, representing Antarctic temperature, is one of the iconic Quaternary records. It shows, in common with other palaeoclimate records such as the marine benthic isotope stack, a dominant 100 ka periodicity of short warm interglacials and long, cold, glacial periods. There appear to be two different styles of interglacial. Within the glacials a millennial scale variability is dominant, manifested as the rapid Dansgaard-Oeschger events in the north, and as subdued out-of-phase counterparts in the south. The trace gases, carbon dioxide and methane, also show a remarkably similar pattern to that of the climate records. They certainly played a role in amplifying small changes in insolation into large climate swings, and their signals are diagnostic of the operation of different processes in the ocean and the terrestrial biosphere.

Introduction

The later parts of the Quaternary have two major advantages for those who want to learn about how the Earth and its climate may evolve in the near future. Firstly, this time provides examples of the operation of a range of processes under boundary conditions (especially the configuration of the continents and of ocean gateways) similar to those of today. Secondly, we have access to much more detailed records of what actually occurred than can be obtained for earlier times. Probably the most potent example of this is the ice cores. They exist only for this period (stretching back now 800 ka in Antarctica (Jouzel et al., 2007) and 123 ka in Greenland (North Greenland Ice Core Project Members, 2004), and they contain not only a climate record for their region, but also concurrent data on climate forcings (especially of greenhouse gases) that have a global reach.

Ice cores can be considered to hold information in three distinct forms. Firstly the isotopic content of the water molecules themselves acts as a proxy for the local temperature above the drilling site. Secondly, many impurities, including aerosol particles and soluble trace gases, are trapped in falling snow or at the snow surface: in this part of the record for example, one can find short spikes of elevated sulfuric acid concentrations corresponding to the years of powerful volcanic eruptions. Finally, snow turns to solid ice in these regions only by sintering under the weight of overlying layers. When this occurs (perhaps 60–100 m below the surface) samples of air are closed off as bubbles that can subsequently be re-opened in order to sample the stable trace gases that were in the atmosphere at the time.

EPICA Dome C and other ice cores

For many years, the oldest ice core record available was the one from Vostok (Petit et al., 1999), collected by Russian, French and US scientists and engineers, and extending back 420 ka. However, the European Project for Ice Coring in Antarctica (EPICA) recently completed the drilling of two ice cores (EPICA Community Members, 2004; EPICA Community Members, 2006), one of which (Dome C) extends the record to 800 ka. In their common parts, Vostok and Dome C (which are about 500 km apart) show almost identical records, and this statement can be extended across the continent to Dome Fuji (Watanabe et al., 2003), where a Japanese team is currently extending the record. Because it is the longest (in age) single record, the rest of this article will concentrate on the data from Dome C.

A critical issue in ice core science (as in other areas of geoscience) is to establish an age scale for the ice. For ice cores in areas with a high snow accumulation rate, it is generally possible to count annual layers using properties that show a regular seasonal cycle. However, of necessity, the cores that span the longest time periods come from regions with very low snow accumulation rates, where this is not possible. At Dome C, the dating is achieved using a physically-based model of snow accumulation and ice thinning rates, constrained and modified by a set of known dates. These constraints derive from a range of sources, culminating in the radiometric date for the Brunhes-Matuyama magnetic reversal, which is represented in the ice core by a peak in concentration of the isotope ^{10}Be (Raisbeck et al., 2006). The current (EDC3) age scale is described in a series of papers and a summary paper (Parrenin et al., 2007).

The Antarctic climate record

The Antarctic deuterium record for the past 800 ka is shown in Figure 1, along with an estimate of Antarctic temperature derived from it (Jouzel et al., 2007), and the classic benthic marine oxygen isotope stack (Lisiecki and Raymo, 2005). The latter record represents a combination of the oxygen isotope content of the ocean (which is controlled by global ice volume), and the fractionating effects of incorporation into shells (which is controlled by deepwater temperature).

The most obvious feature of the past 800 ka is that climate (as represented in both ice and ocean) has a variability dominated by the occurrence of relatively short warm interglacial periods approximately every 100 ka. The Holocene (which we are in now) is the latest of these interglacials. The similarity between the records shows that at these long climate periods we are seeing a global climate signal: when there is more ice in the world, predominantly over North America and Eurasia, there are also colder temperatures in Antarctica. The origin of the 100 ka cyclicity is widely believed to be related to astronomical cycles (Milankovich and related theories) (e.g., Imbrie et al., 1993). However, it remains a matter of debate why the relatively weak 100 ka period is seen more strongly than the precessional (around 20 ka) and obliquity (41 ka) signals that cause

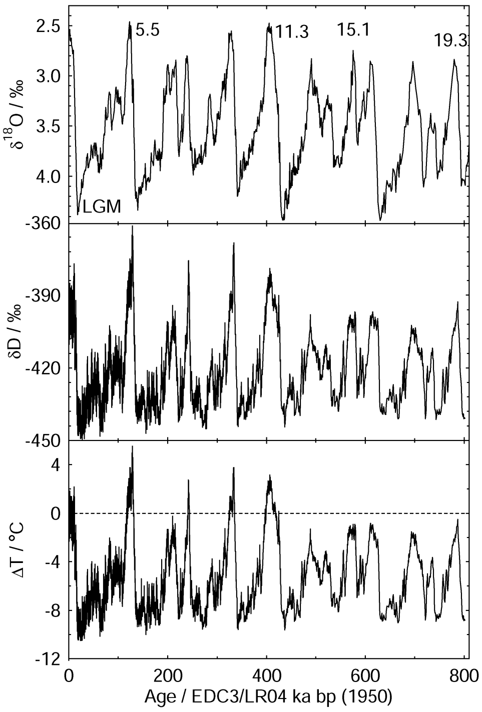

Figure 1 Top panel: Marine benthic oxygen isotope stack on LR04 age scale (Lisiecki and Raymo, 2005); lower panels: 800 ka record, on EDC3 age scale, of deuterium, and temperature (difference from the last millennium, derived using a correction for seawater isotopic content and modelled ice sheet altitude) (Jouzel et al., 2007). Numbers above the marine curve represent selected MIS (marine isotope stages).

larger changes to insolation; and the mechanisms that amplify a small insolation change into a large climate change are also much debated.

Whatever the origin of the 100 ka cyclicity, it is not the case that every cycle is the same. The ice core record has particularly highlighted the differences between different interglacial periods. The 4 interglacials before 450 kyr appear weaker than those that follow, whereas the glacial maxima have less variability in the Antarctic record. The interval between warm periods is also not uniform. No clear explanation for the change in style of interglacial around 450 ka ago has yet emerged (Jouzel et al., 2007).

A final feature that is clear from the Antarctic record is the existence of millennial scale variability, particularly within the glacial periods. The signal has been shown (EPICA Community Members, 2006) to be closely associated with the larger millennial scale variability observed in Greenland (North Greenland Ice Core Project Members, 2004) and other northern hemisphere records, the so-called Dansgaard-Oeschger (D-O) events. These events of rapid warming (more than 10° within decades in Greenland) seem to occur at the apex of slower Antarctic warmings; once Greenland climate has jumped, Antarctic temperature slowly falls again. This pattern has been considered diagnostic of changes in ocean heat transport, with the Southern Ocean building up heat during periods when the heat is not transported northwards (Stocker and Johnsen, 2003). Whatever the cause, this pattern of millennial scale variability is the dominant feature seen in climate records at timescales below those of the orbital cycles.

Trace gases and other signals

As already stated, a unique feature of ice cores is that they contain a direct record of the trace gas content of the atmosphere. CO_2 is obviously a crucial gas for radiative forcing, but is also a diagnostic of

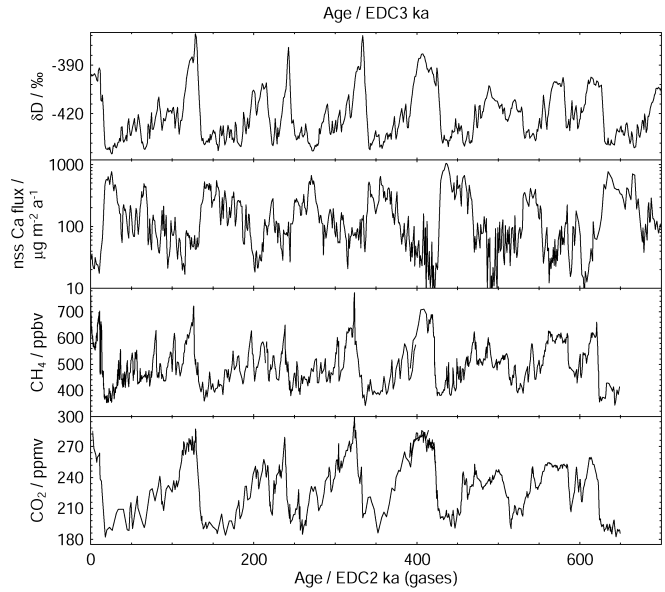

Figure 2 Records of deuterium, non-sea-salt calcium flux (Wolff et al. 2006), CO_2 (Siegenthaler et al. 2005), and CH_4 (Spahni et al. 2005) measured at Dome C. Note that there may be small timing mismatches because the gases are shown on the EDC2 age scale while the other records are on EDC3.

whether we understand the carbon cycle and the oceans that host many aspects of it. CH_4 is another important greenhouse gas, and is also indicative of whether we have correctly assessed aspects of the terrestrial environment. Both gases have so far been reported for the past 650 ka (Figure 2). At the time of writing, the records to 800 ka are being prepared, and tied to the new EDC3 age scale. However, here I show the published data, which are on the old EDC2 age scale and can therefore not be compared directly to the climate record. CO_2 particularly shows (Siegenthaler et al. 2005) a remarkable similarity to Antarctic temperature, with both the glacial-interglacial changes, and the same pattern of interglacials. The CO_2 concentration is typically 280–300 ppmv in warm interglacials, and only 240-250 ppmv in "weak" interglacials. CH_4 also shows (Spahni et al. 2005) a similar pattern, but with a much greater variability at millennial scale within glacial periods, because CH_4 shows up D-O events.

The similarity of CO_2 to Antarctic temperature (without the characteristics more reminiscent of the north) strongly suggests that the Southern Ocean exerts the main control on glacial-interglacial CO_2 changes, although a wide range of physical and biogeochemical processes are still mooted to explain the signal (Archer et al., 2000). Both gases, but particularly CO_2, probably played a significant role in amplifying the small externally-derived insolation changes into the large climate swings that are seen.

It is difficult to derive an exact phasing between changes in temperature and changes in CO_2, because the age of the trapped gas is different from that of the ice that surrounds it. However, for the warming transitions into interglacials, the best estimate (although currently under scrutiny) is that the start of the CO_2 increase lags temperature by around 800 ± 600 years (e.g., Monnin et al., 2001). Because the preceding statement is often misunderstood, it is important to emphasise that the increase in CO_2 and temperature at each termination lasts for around 5 ka. For most of this period, both are rising in parallel, consistent with the idea that, after a small increase in temperature caused by external factors, the two parameters formed an amplifier in positive feedback, with the temperature causing a lagged increase in CO_2, and the CO_2 acting to increase the temperature further.

Many other parameters can be measured on ice cores (as indeed on marine and terrestrial records covering the same period). These give information on aspects of the environment such as sea ice, ocean biogeochemistry and dust transport (Wolff et al., 2006). In

Figure 2, we have included as an example the non-sea-salt Ca flux, which is an indicator of the flux of dust deriving from South America: this record is an important input for studies of dust radiative forcing, and the effects of iron fertilisation of the ocean.

Conclusion

Ice cores are a key data source for the later parts of the Quaternary, providing an anchor of Antarctic temperature and some of the most important forcings. These data, when combined with data from other archives, make this time period highly amenable to modelling and hypothesis testing. The ice core community has formulated ambitious plans for future studies encompassing a range of timescales (Brook and Wolff, 2006). One part of this would aim to find a site where the ice core record could be extended to perhaps 1.5 Ma, and into the section (clearly seen in the marine record) where the 100 ka cycles give way to 40 ka periodicity. Understanding the reason for this change is a key issue in Quaternary science, and discovering how CO_2 and Antarctic climate changed during the transition is widely assumed to be a crucial part of the answer.

References

Archer, D., Winguth, A., Lea, D., and Mahowald, N., 2000, What caused the glacial/interglacial atmospheric pCO(2) cycles?: Reviews of Geophysics, v. 38, pp. 159–189.

Brook, E., and Wolff, E. W., 2006, The future of ice core science: EOS Transactions, v. 87, pp. 39.

EPICA Community Members, 2004, Eight glacial cycles from an Antarctic ice core: Nature, v. 429, pp. 623–628.

-, 2006, One-to-one hemispheric coupling of millennial polar climate variability during the last glacial: Nature, v. 444, pp. 195–198.

Imbrie, J., Berger, A., Boyle, E. A., Clemens, S. C., Duffy, A., Howard, W. R., Kukla, G., Kutzbach, J., Martinson, D. G., McIntyre, A., Mix, A. C., Molfino, B., Morley, J. J., Peterson, L. C., Pisias, N. G., Prell, W. L., Raymo, M. E., Shackleton, N. J., and Toggweiler, J. R., 1993, On the structure and origin of major glaciation cycles. 2. the 100,000-year cycle: Paleoceanography, v. 8, pp. 699–735.

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Nouet, J., Barnola, J. M., Chappellaz, J., Fischer, H., Gallet, J. C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schwander, J., Spahni, R., Souchez, R., Selmo, E., Schilt, A., Steffensen, J. P., Stenni, B., Stauffer, B., Stocker, T., Tison, J.-L., Werner, M., and Wolff, E. W., 2007, Orbital and millennial Antarctic climate variability over the last 800 000 years: Science, v. 317, pp. 793–796.

Lisiecki, L. E., and Raymo, M. E., 2005, A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records: Paleoceanography, v. 20, pp. PA1003; doi:10.1029/2004PA001071.

Monnin, E., Indermuhle, A., Dallenbach, A., Fluckiger, J., Stauffer, B., Stocker, T. F., Raynaud, D., and Barnola, J. M., 2001, Atmospheric CO_2 concentrations over the last glacial termination: Science, v. 291, pp. 112–114.

North Greenland Ice Core Project Members, 2004, High-resolution record of Northern Hemisphere climate extending into the last interglacial period: Nature, v. 431, pp. 147–151.

Parrenin, F., Barnola, J. M., Beer, J., Blunier, T., Castellano, E., Chappellaz, J., Dreyfus, G., Fischer, H., Fujita, S., Jouzel, J., Kawamura, K., Lemieux, B., Loulergue, L., Masson-Delmotte, V., Narcisi, B., Petit, J. R., Raisbeck, G., Raynaud, D., Ruth, U., Schwander, J., Severi, M., Spahni, R., Steffensen, J. P., Svensson, A., Udisti, R., Waelbroeck, C., and Wolff, E. W., 2007, The EDC3 chronology for the EPICA Dome C ice core: Climate of the Past, v. 3, pp. 485–497.

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J. M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., and Stievenard, M., 1999, Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica: Nature, v. 399, pp. 429–436.

Raisbeck, G. M., Yiou, F., Cattani, O., and Jouzel, J., 2006, 10Be evidence for the Matuyama-Brunhes geomagnetic reversal in the EPICA Dome C ice core: Nature, v. 444, pp. 82–84.

Siegenthaler, U., Stocker, T. F., Monnin, E., Luthi, D., Schwander, J., Stauffer, B., Raynaud, D., Barnola, J. M., Fischer, H., Masson-Delmotte, V., and Jouzel, J., 2005, Stable carbon cycle-climate relationship during the late Pleistocene: Science, v. 310, pp. 1313–1317.

Spahni, R., Chappellaz, J., Stocker, T. F., Loulergue, L., Hausammann, G., Kawamura, K., Flückiger, J., Schwander, J., Raynaud, D., Masson-Delmotte, V., and Jouzel, J., 2005, Atmospheric methane and nitrous oxide of the late Pleistocene from Antarctic ice cores: Science, v. 310, pp. 1317–1321.

Stocker, T. F., and Johnsen, S. J., 2003, A minimum thermodynamic model for the bipolar seesaw: Paleoceanography, v. 18, pp. art. no.-1087.

Watanabe, O., Jouzel, J., Johnsen, S., Parrenin, F., Shoji, H., and Yoshida, N., 2003, Homogeneous climate variability across East Antarctica over the past three glacial cycles: Nature, v. 422, pp. 509–512.

Wolff, E. W., Fischer, H., Fundel, F., Ruth, U., Twarloh, B., Littot, G. C., Mulvaney, R., Rothlisberger, R., de Angelis, M., Boutron, C. F., Hansson, M., Jonsell, U., Hutterli, M. A., Bigler, M., Lambert, F., Kaufmann, P., Stauffer, B., Stocker, T. F., Steffensen, J. P., Siggaard-Andersen, M. L., Udisti, R., Becagli, S., Castellano, E., Severi, M., Wagenbach, D., Barbante, C., Gabrielli, P., and Gaspari, V., 2006, Southern Ocean sea-ice extent, productivity and iron flux over the past eight glacial cycles: Nature, v. 440, pp. 491–496.

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by Andrey E. Dodonov[1] and Liping Zhou[2]

Loess deposition in Asia: its initiation and development before and during the Quaternary

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Dust is important in the Earth environment system. However, the role of dust in climate change remains largely unknown. A better understanding of the temporal and spatial variability of the dust accumulation in Asia forms an important step towards establishing the link between dust deposition and climate change. Here, a summary is given for the timing of the onset and expansion of loess deposition in Asia beginning in the early Miocene. Recent progress on some aspects of loess chronology and palaeoenvironmental reconstruction is also reviewed.

Introduction

Loess is a very characteristic sedimentary unit in Asia, providing enormous archives for the geological history of the Quaternary. Loess areas of Asia are highly populated regions with intensively developed agriculture, large towns, industrial and hydrological constructions.

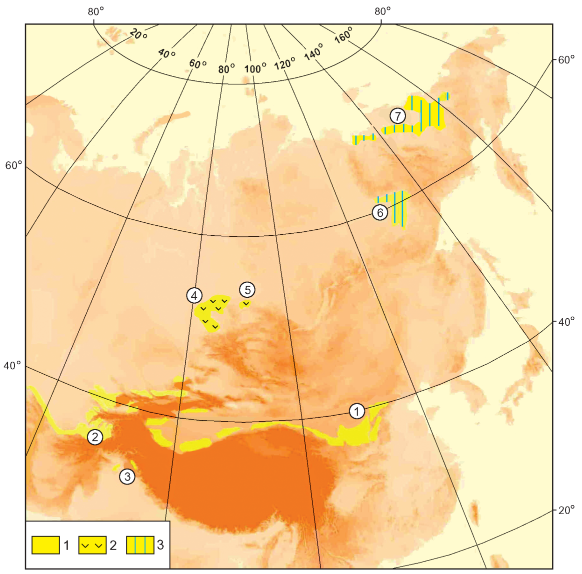

***Figure 1** Schematic map showing distribution of loess and loesslike deposits in Asia.*
1–loess of arid zone; 2–loess and loesslike silt in periglacial zone; 3–loess and loesslike silt with inclusion of ice in subarctic zone. Regions of loess and loesslike silts referred in the paper (figures in circles): 1–Loess Plateau of Northern China; 2–Central Asia, Tadjikistan; 3–Central Asia, Kashmir Valley, Peshavar Basin, Potvar Palteau; 4–Ob' Plateau of south Western Sibereia; 5–Kurtak region in the Enisei Valley of south Eastern Siberia; 6–Central Yakutiya; 7–Northern Yakutiya.

Loess studies of Asia are associated with famous names such as von Richthofen, Obruchev, Pavlov, Liu Tungsheng, Kriger and others (Smalley et al., 2001), who pioneered fundamental studies of loess origin, lithologic characteristics, and deposition processes. Many properties of loess, such as high permeability, loose structure, erosive capability, collapsibility, suffosion, landsliding, and underflooding pose huge challenges to the people living in loess regions.

As a great subcontinent, Asia is characterized by extremely continental climatic conditions in the central part, as well as significant regional changes from the north to the south. These features define a considerable diversity of loess sequences from the arid zone in Central Asia and North China to the periglacial zone in South Siberia, and subarctic frozen loess zone in Central and Northern Yakutiya (Figure 1).

Intensive investigations have been undertaken in order to understand the paleoenvironmental significance of the loess formation in different parts of Asia. Nevertheless, some of the fundamental scientific questions remain outstanding: When did loess accumulation start in Asia? What were the controlling factors for the initiation of loess accumulation? Where did the silty materials come from? And what was the relationship between dust deposition and climate in the past? Here we provide an overview of some of the recent development in loess research with particular reference to the pattern of initial loess deposition across Asia.

The onset and expansion of aeolian deposition in different parts of Asia

Northern China and Central Asia are characterized by the most complete known loess strata, embracing Quaternary time back to ca. 2.6 Ma (Liu et al., 1985; Kukla and An, 1989; Rutter et al., 1991; Ding et al., 2002; Dodonov, 1991, 2002). Due to the lack of any features that are characteristic of cryogenic processes, loess here is considered as "warm-climate" loess with dominant sources from desert or dryland (Smalley et al., 2001). With the intensive investigation of the Red Clay at Xian, Xifeng, Lingtai and Jiaxian of Chinese Loess Plateau, the start of aeolian deposition in Asia was extended to 7–8 Ma (Liu et al., 1991; Sun et al., 1998; Ding et al., 1999; Qiang et al., 2001). New data from the southwestern part of the Loess Plateau point to even earlier aeolian deposition in northern China (Figure 2), extending back to the Lower-Middle Miocene (Guo et al., 2002; Qiao et al., 2006). An important implication of this new finding is that desert dust sources were developed since the Miocene and arid conditions, dust deflation and aeolian accumulation became a characteristic of the environment from that time. Another implication is concerned with the wind systems responsible for the transport of the dust materials. In China, this would be related to the development of monsoonal system (e.g., An, 2000; Guo et al., 2002).

During the Pliocene and Pleistocene, neotectonic uplift of the Tibetan Plateau, Himalayas and Tian Shan mountains (Liu and Ding, 1984; Burbank and Raynolds, 1984; Chadiya, 1986; Li et al., 1995; Dodonov, 2002) caused more isolation of internal parts of Central Asia and stimulated desiccation of the regional climate. It is conceiv-

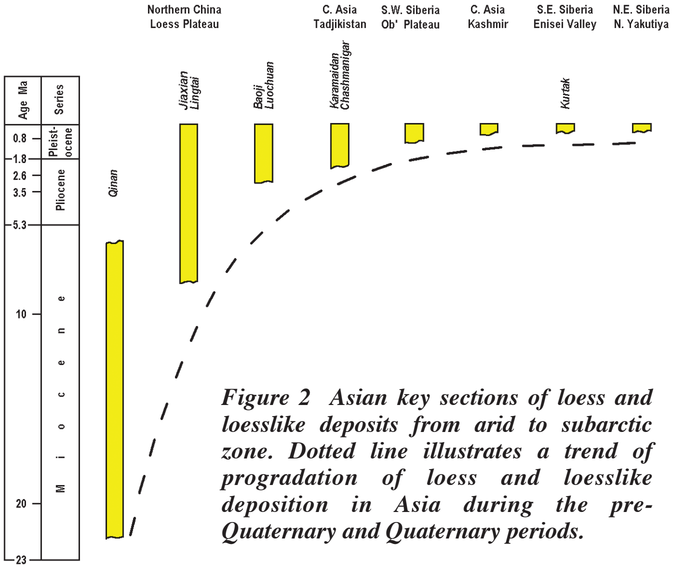

Figure 2 Asian key sections of loess and loesslike deposits from arid to subarctic zone. Dotted line illustrates a trend of progradation of loess and loesslike deposition in Asia during the pre-Quaternary and Quaternary periods.

able that such a change in landform and climate has formed the background for the large-scale dust generation and deposition in Asia. The distribution of Miocene aeolian deposits is mostly confined to the west of the Liupan Mountain probably constrained by geomorphic conditions. The subsequent Pliocene aeolian deposits were spread into wider areas in the Loess Plateau but still mostly confined to areas which had favourable conditions for dust trapping. The cause for the expansion has yet to be established. In Central Asia, the Early Pleistocene was a crucial time when loess became one of the dominat types of sedimentation in Northern China and Tadjikistan. Further enlargement of the arid area and development of more favorable conditions for loess aggradation in the Middle and Late Pleistocene widened loess distribution, resulting in spatial expansion of loess provinces to the Kashmir Valley, Peshavar Basin and Potvar Plateau where loess sequences are dated from the Middle to Late Pleistocene (Bronger et al., 1987; Singhvi et al., 1987; Rendell, 1988). In south Western Siberia, loess accumulation began in the early Middle Pleistocene (Zykina, 1999). This area belongs to the periglacial zone where loess is considered as "cold-climate" loess with many traces of cryogenic effects (Smalley, 1995; Smalley et al., 2001). Another super-cold subarctic area, situated further to the north, became more arid at the end of Middle Pleistocene and in the Late Pleistocene (Figure 2). In Northern Siberia, desiccation and freezing processes during the Last Glacial Maximum led to widespread production of fine-grained sediments as loess or loesslike silt with inclusion of thick syngenetic polygonal ice wedges sometimes reaching up to 70–80% of the sediment volume. Because of their unusually high ice content, these deposits are known as the 'loess-ice complex', 'ice complex', or 'edoma' (Tomirdiaro, 1980; Kaplina and Lozhkin, 1984). 'Edoma' sediments or frozen loess (loesslike silt) is typical of the Yana-Indigirka and Kolyma lowlands in north Eastern Siberia. An aeolian origin has been hypothesised as an alternative to a fluvial and polygenetic origin (Tomirdiaro, 1980). On the Quaternary map of Russia (2001), the areas covered by ice-rich loess (loess containing ice) are shown in the Yana-Indigirka Plain of Northern Yakutiya. In Central Yakutiya, loesslike silt mantles form a blanket on river terraces and upland surface of irregular topography. The aeolian origin of this silt was long disputed but has gained strong support in later studies (e.g., Péwé and Journaux, 1983).

Chronological framework

One of the key issues in loess study and paleogeographic reconstruction is the stratigraphic correlation between different zones. This has been achieved by numerical dating and by means of long-term climate variability recorded in the loess sequences. Paleoclimatic fluctuations are manifested in loess strata as the alternation of soil and loess horizons, which serve as key markers for detailed subdivision and correlation (Derbyshire et al., 1995). Paleomagnetic measurements, tied to the Geomagnetic Polarity Time Scale provide valuable geochronological controls. The Gauss/Matuyama reversal (~2.6 Ma) falls near the lithological transition between the Red Clay strata and overlying Wucheng Loess at the level of loess horizon L33 in most of the Chinese sections, for example Xian, Xifeng, Lingtai and Jiaxian (Liu et al., 1991; Sun et al., 1998; Ding et al., 1999, Qiang et al., 2001). In Central Asia, in Tadjikistan, the Gauss/Matuyama boundary was determined at the base of loess stratum in the most complete loess section of Karamaidan (Dodonov, 2002).

Another chronostratigraphic marker, the Matuyama/Brunhes (M/B) reversal (~0.78 Ma), is also very useful for correlation of the Middle and Upper Pleistocene loess series. In the Loess Plateau, the M/B reversal is located between paleosols S8 and S7 (Heller and Liu, 1984). In Tadjikistan, the M/B reversal is located in the loess horizon between tenth and ninth pedocomlexes (PC), or at the base of PC9 (Dodonov and Pen'kov, 1977; Dodonov, 1991; Forster and Heller, 1994). As in Tadjikistan, in the Ob' Plateau of south Western Siberia, nine major pedocomplexes and loess units are present in loess deposits above the M/B boundary (Zykina, 1999). It should be noted that the measured positions of the M/B and other geomagnetic reversals in loess may be variably affected by the lock-in effect of the magnetic remanence (e.g., Zhou and Shackleton, 1999) although there is still difference in the understanding of the disparity in M/B boundary between the loess and marine geomagnetic records (e.g., Spassov et al., 2003; Wang et al., 2006). The varying displacement could introduce significant uncertainty in loess stratigraphical correlation. The uncertainty may become strikingly larger when loess records are correlated with marine and ice isotope records.

For the youngest parts of loess sequences, luminiscence dating has become a major tool in establishing chronology for the Late Pleistocene (Murray and Wintle, 2000; Roberts and Wintle, 2001; Zhou and Shackleton, 2001; Stevens et al., 2006; Lai et al., 2007). The Last Interglacial soil horizon, S1 in Chinese sections, PC1 in Tadjikistan and Kurtak paleosol in south Eastern Siberia is dated in the range of 130–70 ka, corresponding to the entire MIS 5 (Liu et al., 1985; Zhou et al., 1995; Frechen and Dodonov, 1998; Frechen et al., 2005). This serves as an important time marker in loess stratigrphy. Recent optically stimulated luminescence studies show significant age underestimation for some of the late Pleistocene loess from China (e.g., Qin and Zhou, 2007; Buylaert et al., 2008). However, the precise extent of uncertainty in chronology may vary for different loess regions and has been hard to establish due to the lack of other dating materials. This requires further investigation.

Diversity in magnetic susceptibility records

Variations in magnetic susceptibility of loess-paleosol sequences have been shown to track the development of the pedogenetic processes that depend on paleoclimatic conditions during the Quaternary (Zhou et al., 1990; Heller et al., 1991; Maher and Thompson, 1991; Forster and Heller, 1994; Shackleton et al., 1995, An, 2000; Ding et al., 2002). It has been one of the most commonly used tools for stratigraphical correlation as well as for paleoenvironmental reconstruction. The magnetic susceptibility of loess and paleosols from northern China and Tadjikistan show remarkable coherence with the oxygen isotope record of the deep sea cores with higher magnetic susceptibility values in paleosols and lower values in loess due to pedogenic enhancement during relatively wetter and warmer intervals (Forster and Heller, 1994; Shackleton et al., 1995; Ding et al., 2002). Note, however, the two regions are under different climate regimes, i.e. being monsoonal and non-monsoonal. The Siberian loess-paleosol succession has completely opposite magnetic susceptibility pattern. Here a gradual magnetic mineral depletion occurs during soil formation which, when coupled with more intense wind activity during the cold intervals (leading to accumulation of greater quantities of larger ferromagnetic grains) gives higher magnetic susceptibility values in the loess (Chlachula, 1999; Zhu et al., 2003). The paleoclimatic interpretation of magnetic susceptibility of pre-Quaternary loess or loesslike deposits is more complicated and should be made with caution (Ding et al., 1998; Liu et al., 2003).

Sedimentation rate

The intensity of the aeolian dust sedimentation has generally increased during the Quaternary (Dodonov, 2002). For example, based on magnetostratigraphy, an average dust accumulation rate of approximately 1.67 cm/kyr was obtained for the Qinan Miocene subaerial section in southwestern Loess Plateau (Guo et al., 2002). The Red Clay (Red-Earth) formation, characterized mostly by aeolian derived particle size composition especially for its Pliocene middle and upper parts, accumulated at an average rate of 1.5–3.5 cm/kyr (Guo et al., 2001). The average rate for loess sedimentation in South Tajikistan was in the range of 6 cm/kyr in the Lower Pleistocene, increased during the Middle Pleistocene and attained rates of 40–50 cm/kyr to the Late Pleistocene during the Last Glacial Maximum (Dodonov, 2006). The average loess accumulation in China, at Luochuan section, changes from 4.5 cm/kyr below the Jaramillo Subchron (1.07–0.99 Ma) to 7.5–10 cm/kyr in the upper part of the sections (Heller and Liu, 1984). Thus, it appears that similar, proportional changes of loess sedimentation rates have occurred in different loess provinces. This suggests that the general pattern in the development of aeolian processes across different regions of Asia might have been determined by progressive, continent-wide paleoclimatic changes.

Definition of ancient aeolian deposits

At the moment, the aeolian deposits from northern China have been given different identities such as loess, red clay and Miocene loess. In the context of identifying early loess deposition, Pécsi's opinion should be mentioned. He suggested that “Wucheng loess” can not be considered as typical loess due to significant difference in lithological properties in comparison with younger Lishi loess (Pécsi, 1987). Whether the term loess can be used for ancient Miocene and Pliocene parts of the Chinese sections, e.g., at Qinan, Lingtai, Xifeng and others is still a matter for discussion because the strata contain thin dispersed sediments that have lost some of the features characteristic of typical loess. A clarification of the nomenclature may therefore help to understand the processes and environments during the loess formation.

Concluding remarks

In summary, the distribution, characteristics and age of loess or loesslike silts since the Miocene allows reconstruction of the general trends of environmental changes and the loess progradation in Asia from the most arid areas in the central parts to the temperate and high latitudes of the subcontinent (Figure 2). The initial accumulation of loess in Asia is associated with the neotectonic uplift of the main mountain systems in Central Asia which caused significant aridification of this region. Quaternary glaciations further increased desiccation in the different zones from the south to the north. The characteristic lithological features of loess and loesslike deposits in the different zones thus reflect the specific environmental conditions that were developed *prior to* and during the Quaternary. As Asian loess deposits occur under both monsoonal and non-monsoonal climates, loess sequences in Asia therefore can serve as long-term records of different climate regimes.

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References

An Z.S., 2000, The history and variability of the East Asian paleomonsoon climate: Quaternary Science Reviews, 19, pp. 171–187.

Bronger A., Pant R.K., and Singhvi A.K., 1987, Micromorphology, mineralogy, genesis and dating of loess-paleosol sequences and their applicaton to Pleistocene chronostratigraphy and paleoclimate: A comparison between southeast Central Europe and the Kashmir Valley/Central Asia. Aspects of loess research. Beijing: China Ocean Press, pp. 121–129.

Burbank D.W. and Raynolds R.G.H., 1984, Sequential late Cenozoic structural disruption of the northern Himalayan foredeep: Nature, 311, pp. 114–118.

Buylaert J.P., Murray A.S., Vandenberghe D., Vriend M., De Corte F., Van den Haute P., 2008, Optical dating of Chinese loess using sand-sized quartz: Establishing a time frame for Late Pleistocene climate changes in the western part of the Chinese Loess Plateau: Quaternary Geochronology, 3, pp. 99–113.

Chadiya O.K., 1986, Morphostucture and newest tectogenesis of Tian Shan. Frunze. ILIM. 314 pp. (In Russian).

Chlachula J., 1999, Loess-paleosol stratigraphy in the Yenisey basin, Southern Siberia. Eds. J.Chlachula, R.A.Kemp, and J.Tyraček, Quaternary of Siberia: Journal of Geological Sciences, 23. Prague, pp. 55–70.

Derbyshire E., Kemp R., and Meng X.M., 1995, Variations in loess and paleosol properties as indicators of paleoclimatic gradients across the Loess Plateau of north China: Quaternary Science Reviews, 14, pp. 681–697.

Ding Z.L., Sun J.M., Liu T.S., Zhu R.X., Yang S.L., Guo B., 1998, Windblown origin of the Pliocene red clay formation in the central Loess Plateau, China: Earth and Planetary Science Letters, 161, pp. 135–143.

Ding Z.L., Xiong S.F., Sun J.M., Yang S.L., Gu Z.Y., and Liu T.S., 1999, Pedostratigraphy and paleomagnetism of a ~ 7.0 Ma aeolian loess-red clay sequence at Lingtai, Loess Plateau, north-central China and the implications for paleomonsoon evolution: Palaeogeography, Palaeoclimatology, Palaeoecology, 152, pp. 49–66.

Ding Z.L., Ranov V., Yang S.L., Finaev A., Han J.M., Wang G.A., 2002, The loess record in southern Tajikistan and correlation with Chinese loess: Earth and Planetary Science Letters, 200, pp. 387–400.

Dodonov A.E., 1991, Loess of Central Asia: Geol. Rundsch. 24, pp. 185–194.

Dodonov A.E., 2002, Quaternary of Middle Asia. Stratigraphy, correlation, paleogeography. Moscow. GEOS. 250 pp. (In Russian).

Dodonov A.E., 2006, Loess Records. Central Asia. Encyclopedia of Quaternary Science. Elsevier, Vol. 2, pp. 1418–1429.

Dodonov A.E. and Pen'kov A.V., 1977, Some data on the stratigraphy of the watershed loesses in Tadjik Depression: Bulletin of the Commission on the Quaternary Research, 47, pp. 67–76. (In Russian).

Forster Th. and Heller F., 1994, Loess deposits from the Tadjik depression (Central Asia): Magnetic properties and paleoclimate: Earth and Planetary Science Letters, 128, pp. 501–512.

Frechen M. and Dodonov A.E., 1998, Loess chronology of the Middle and Upper Pleistocene in Tadjikistan:. Geol. Rundsch. 87, pp. 2–20.

Frechen M., Zander A., Zykina V., and Boenigk W., 2005, The loess records from the section at Kurtak in Middle Siberia: Palaeogeography, Palaeoclimatology, Palaeoecology, 228, pp. 228–244.

Guo Z.T., Peng S.Z., Hao Q.Z., Biscaye P.E., and Liu T.S., 2001, Origin of the Miocene-Pliocene Red-Earth Formation at Xifeng in Northern China and implications for paleoenvironments: Palaeogeography, Palaeoclimatology, Palaeoecology, 170, pp. 11–26.

Guo Z.T., Ruddiman W.F., Hao Q.Z., Wu H.B., Qiao Y.S., Zhu R.X., Peng S.Z., Wei J.J., Yuan B.Y., and Liu T.S., 2002, Onset of Asian desertification by 22Myr ago inferred from loess deposits in China: Nature, 416, pp. 159–163.

Heller F., Liu T., 1984, Magnetism of Chinese loess deposits: Geophys. J. R. astr. Soc. 77, pp. 125–141.

Heller F., Liu X., Liu T., and Xu T., 1991, Magnetic susceptibility of loess in China: Earth and Planetary Science Letters, 103, pp. 301–310.

Kaplina T.N. and Lozhkin A.V., 1984, Age and history of accumulation of 'ice complex' of the maritime lowlands of Yakutyiya, *in*: Ed. A.A.Velichko, Late Quaternary environments in the Soviet Union: Longman. London, pp. 147–151.

Kukla G. and An Z., 1989, Loess stratigraphy in Central China: Palaeogeography, Palaeoclimatology, Palaeoecology, 72, pp. 203–225.

Lai Z.P., Wintle A.G., Thomas D.S.G., 2007, Rates of dust deposition between 50 ka and 20 ka revealed by OSL dating at Yuanbao on the Chinese Loess Plateau: Palaeogeography, Palaeoclimatology, Palaeoecology, 248, pp. 431–439.

Li J. et al., 1995, Uplift of Qinghai-Xizang (Tibet) Plateau and global change: Lanzhou University Press. 207 pp.

Liu T.S. and Ding M., 1984, The characteristics and evolution of the palaeoenvironment of China since the Late Tertiary, *in*: The evolution of the East Asian environment, Proc. Int. Conf. Vol. 1: Geology and Palaeoclimatology. Hong Kong, pp. 11–40.

Liu T.S. et al., 1985, Loess and the environment: China Ocean Press, Beijng. 251 pp.

Liu X., Liu T.S., Shaw J., Heller F., Xu T., and Yuan B., 1991, Paleomagnetic and paleoclimatic studies of Chinese loess, *in*: Ed. Liu T.S., Loess, environment and global change: Science Press, Beijing, pp. 61–81.

Liu X.M., Rolph T., An Z.S., Hesse P., 2003, Paleoclimatic significance of magnetic properties on the Red Clay underlying the loess and paleosols in China: Palaeogeography, Palaeoclimatology, Palaeoecology, 199, pp. 153–166.

Maher B.A., Thompson R., 1991, Mineral magnetic record of the Chinese loess and paleosols: Geology 19, pp. 3–6.

Murray A.S., Wintle A.G., 2000, Luminescence dating of quartz using an improved single-aliquot regenerative dose protocol: Radiation Measurements, 2000, 32, pp 57–73.

Pécsi M., 1987, International Loess Symposium in China, Xian, Shaanxi Province, October 15–16, 1985: GeoJornal, 14, 4, pp. 435–445.

Péwé T.L. and Journaux A., 1983, Origin and character of loesslike silt in unglaciated South-Central Yakutia, Siberia, U.S.S.R. Geological Survey professional paper, 1262. US Government Printing Office, Washington. 46 pp.

Qiang X.K., Li Z.X., Powell C.McA, Zheng H.B., 2001, Magnetostratigraphic record of the Late Miocene onset of the East Asian monsoon, and Pliocene uplift of northern Tibet: Earth and Planetary Science Letters, 187, pp. 83–93.

Qiao Y., Guo Z., Hao Q., Yin Q., Yuan B., and Liu T., 2006, Grain-size features of a Miocene loess-soil sequence at Qinan: Implications on its origin: Science in China. Ser. D, Earth Science, 49, 7, pp. 731–738.

Qin J.T. and Zhou L.P., 2007, Optically Stimulated Luminescence Dating of Upper Part of a Thick Loess Section at Caoxian near the Northern Desert of China: Quaternary Sciences, 27, pp.546–552. (Chinese with English abstract).

Quaternary map of Russia, 1:5 000 000, 2001, Eds. I.I.Krasnov, B.A.Borisov, and E.A.Minina. All Russian Geological Research Institute (VSEGEI). St. Petersburg.

Rendell H., 1988, Environmental changes during the Pleistocene in the Potwar Plateau and Peshawar Basin, Northern Pakistan. Paleoclimatic and paleoenvironmental changes in Asia during the last 4 million years: New Delhi, Indian National Sci. Acad., pp. 58–66.

Roberts H.M., Wintle A.G., 2001, Equivalent dose determinations for polymineralic fine-grains using the SAR protocol: Application to a Holocene sequence of the Chinese Loess Plateau: Quaternary Science Reviews, 2001, 20, pp. 859–863.

Rutter N., Ding Z., and Liu T., 1991, Comparison of isotope stages 1–61 with the Baoji-type pedostratigraphic section of north-central China: Canadian Journal of Earth Sci., 28, pp. 985–990.

Shackleton N.J., An Z., Dodonov A.E., Gavin J., Kukla G.J., Ranov V.A., and Zhou L.P., 1995, Accumulation rate of loess in Tadjikistan and China: Relationship with global ice volume cycles: Quaternary Proceedings, 4, pp. 1–6.

Singhvi A.K., Bronger A., Pant R.K., and Sauer W., 1987, Thermoluminescence dating and its implication for the chronostratigraphy of loess-paleosol sequences in the Kashmir Valley (India): Chemical Geology, 65, pp. 45–56.

Smalley I., 1995, Making the material: The formation of silt sized primary mineral particles for loess deposits: Quaternary Science Reviews, 14, pp. 645–651.

Smalley I.J., Jefferson I.F., Dijkstra T.A., Derbyshire E., 2001, Some major events in the development of the scientific study of loess: Earth-Science Reviews, 54, pp. 5–18.

Spassov, S., Heller, F., Evans, M.E.,Yue, L.P., von Dobeneck, T., 2003. A lock-in model for the complex Matuyama/Brunhes boundary record of the loess/paleosol sequence at Lingtai (Central Chinese Loess Plateau): Geophys. J. Int., 155, pp. 350–366.

Stevens T., Armitage S.J., Lu H.Y., and Thomas, D.S.G., 2006, Sedimentation and diagenesis of Chinese loess: Implications for the preservation of continuous, high resolution climate records: Geology, 34, pp. 849–852.

Sun, D.H., Shaw, J., An, Z.S., Cheng, M., Yue, L.P., 1998, Magnetostratigraphy and paleoclimatic interpretation of a continuous 7.2 Ma Late Cenozoic eolian sediments from the Chinese Loess Plateau: Geophys. Res. Lett. 25, pp. 85–88.

Tomirdiaro S.V., 1980, Loess-ice formation of Eastern Siberia during the Late Pleistocene and Holocene: Moscow, Nauka, 184 pp. (In Russian).

Wang X.S., Yang Z.Y., Løvlie R., Sun Z.M., Pei J.L., 2006. A magnetostratigraphic reassessment of correlation between Chinese loess and marine oxygen isotope records over the last 1.1 Ma: Phys.Earth Planet. Int., 159, pp. 109–117.

Zhou L.P., Dodonov A.E., and Shackleton N.J., 1995, Thermoluminescence dating of the Orkutsay loess section in Tashkent Region, Uzbekistan, Central Asia: Quatenary Science Reviews, 14, pp. 721–730.

Zhou L.P., Oldfield F., Wintle A.G., Robinson S.G. and Wand J.T., 1990, Partly pedogenetic origin of magnetic variations in Chinese loess: Nature, 346, pp. 737–739.

Zhou L.P. and Shackleton N.J., 1999, Misleading positions of geomagnetic reversal boundaries in Eurasia loess and implications for correlaton between continental and marine sedimentary sequences: Earth and Planetary Science Letters, 168, pp. 117–130.

Zhou L.P. and Shackleton N.J., 2001, Photon stimulated luminescence of quartz from loess and effects of sensitivity change on palaeodose determination: Quaternary Science Reviews, 20, pp. 853–857.

Zhu R.X., Matasova G., Kazansky A., Zykina V., Sun J.M., 2003, Rock magnetic record of the last glacial-interglacial cycle from the Kurtak loess section, southern Siberia: Geophysical Journal International, 152, pp. 335–343

Zykina V.S., 1999, Pleistocene pedogenesis and climatic history of Western Siberia. Eds. J.Chlachula, R.A.Kemp, and J.Tyraček, Quaternary of Siberia: Journal of Geological Sciences, 23. Prague, pp. 49–54.

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Editor's note: Since completing this article Dr Andrey Dodonov died following a heart attack on 7 May. He will be greatly missed by his colleagues.

by Wim Z. Hoek

The Last Glacial-Interglacial Transition

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The Last Glacial-Interglacial Transition is one of the most intensively studied periods in Earth History. The rapid climate and environmental changes that occurred during the transition can be used to test ideas about the functioning of our climate system. The stratigraphy of this period has been thoroughly investigated and, in particular, the recently proposed event stratigraphy for the Last Glacial-Interglacial Transition based on the Greenland ice core records serves as a tool for synchronisation of records from the ice, marine and terrestrial environment. The causes behind the rapid climate changes are most likely to have been changes in ocean circulation, partly triggered by ice-melting during deglaciation. While the picture for the North Atlantic region is becoming more and more clear, complex patterns of change over the globe remain to be studied. The functioning of the complex feed-back mechanisms requires an interdisciplinary approach between geoscientists from different disciplines.

Introduction

The Last Glacial-Interglacial Transition (LGIT), often referred to as Weichselian Lateglacial or Last Termination (ca 13,000–10,000 ^{14}C yrs BP), marks the transition from the cold Weichselian Glacial to the warm Holocene. The LGIT is classically sub-divided into a series of cold stadials such as the Younger Dryas Stadial (named after the occurrence of the characteristic arctic-alpine plant species *Dryas octopetala*) separated by warm interstadials named after the type localities Bølling and Allerød in Denmark. This climatostratigraphic sub-division has been extensively used in NW-Europe, usually in a chronostratigraphic sense, and is still widely employed globally.

The rapid climate changes that occurred during the LGIT, have stimulated the palaeoclimate research community to study this period intensively. This is not only because it provides the opportunity to investigate the nature of the climate changes in high-resolution, but also to test hypotheses on the mechanisms behind the abrupt changes using palaeoclimate modelling. This makes the LGIT one of the most thoroughly investigated of all geological episodes. As a result, the stratigraphy of this time period is relatively well developed.

History

In 1901, Hartz and Milthers used deposits in a clay-pit near Allerød (Denmark) to demonstrate that a climatic warming occurred during the Lateglacial. Between two clay layers containing leaves of mountain avens (*Dryas octopetala*) and fossils of reindeer (*Rangifer tarandus*), an organic layer with birch remains (*Betula* spp.) and fossils of the European elk (*Alces alces*) was present, indicating a change from tundra to a more forested environment followed by a return to tundra. Based on palynology, Jessen (1935) was able to define three successive pollen zones: Early Dryas (I), Allerød (II), and Late Dryas (III). This subdivision was further refined by Iversen (1942), who added another interstadial phase that supposedly occurred before the Allerød and was based on evidence from the site at Bølling Sø (Denmark).

The palynological sub-division of the Weichselian Late Glacial established by Jessen (1935) and Iversen (1942), was introduced into The Netherlands by van der Hammen (1949), who recognized the Bølling and Allerød oscillations, separated by the colder Dryas stadials in the lake deposits of Hijkermeer. The interstadial deposits were characterised by a higher content of organics in comparison with the stadial deposits. Van der Hammen (1951) went on to demonstrate a similar vegetation development at different locations in The Netherlands and nearby areas. In Central Europe, the scheme described by Firbas (1954) has been more widely used. His definition, particularly of the Oldest Dryas which is not so characteristic in NW Europe, has continued to be used in the Alpine region. Since then, hundreds of pollen diagrams from Late Glacial deposits have been constructed using the subdivisions suggested by van der Hammen and Firbas.

Chronostratigraphy of the Last Glacial Interglacial Transition

With the introduction of the radiocarbon dating method, biostratigraphic correlation became less important and pollen diagrams were considered more frequently in a chronological context. Moreover, the terminology that was originally developed for biostratigraphical zones (Bølling, Allerød, etc.) has been used throughout northern and western Europe in a chronostratigraphic sense (Mangerud et al., 1974). Since then, the terms Bølling and Allerød have been connected worldwide to the time period between 13,000 and 11,000 ^{14}C yr BP as defined by Mangerud et al. (1974), while the Younger Dryas chronozone falls between 11,000 and 10,000 ^{14}C yr BP (Table 1). This chronological subdivision was initially based on the radiocarbon dated biostratigraphic zone boundaries from southern Scandinavia, and predated important later advances in radiocarbon dating such as AMS and radiocarbon calibration.

Bio- and chronostratigraphy

Boundaries of similar biostratigraphical zones defined in different regions are in most cases diachronous due to differences in biological response to changes in climate. This means that the biostratigraphic zones as defined in Scandinavia are difficult to apply outside this geographical region. Terms such as Lateglacial Interstadial or Windermere Interstadial have been used for the Bølling-Allerød interstadial complex in Britain, where it is often difficult to recognize stadial conditions between the two separate interstadial phases. Furthermore, there are problems relating to biostratigraphic

Table 1 Chronostratigraphy of the Late Weichselian based on the classical Stratigraphy of Norden after Mangerud et al.

chronozone	^{14}C age BP
FLANDRIAN (HOLOCENE)	
	10,000
Younger Dryas	
	11,000
Allerød	
	11,800
Older Dryas	
	12,000
Bølling	
	13,000
MIDDLE WEICHSELIAN	

definition. In Germany, an additional interstadial called Meiendorf has often been recognized, which correlates to the Bølling interstadial in the surrounding countries. But in this particular case, the term Bölling is used for what is effectively the first part of the Allerød interstadial in the surrounding countries, leading to considerable confusion. This apparent discrepancy between the definition of Bølling and Allerød is mainly the result of a difference of opinion over correlation by Iversen (1942) with the section at Bølling Sø (de Klerk, 2004). These examples highlight some of the problems of transferring a biostratigraphic zonation scheme from one region to another.

The chronostratigraphic approach, originally developed for Scandinavia, can be compared to that in other areas of northwest Europe, and again differences emerge. In The Netherlands, for example, where there are a number of ^{14}C -dated Lateglacial pollen diagrams, the onset of the Lateglacial Interstadial falls between 12,500 and 12,450 ^{14}C yrs BP (Hoek, 2001). This is considerably later than the start of classically defined Bølling in Scandinavia (Table 1). The start and end of the Younger Dryas Stadial in the Netherlands, however, have been dated at 10,950 and 10,150 ^{14}C yrs BP, respectively, and are more in accordance with the chronostratigraphic boundaries defined by Mangerud et al. (1974).

Event stratigraphy

As mentioned above, the application of biostratigraphic terminology to records from different regions and different spheres often cause correlation problems.

In an attempt to resolve some of these difficulties, the INTIMATE group of the INQUA Palaeoclimate Commission developed an Event Stratigraphy for the North Atlantic region, based on the Greenland ice-core record (Björck et al., 1998; Walker et al., 1999). This scheme defines a series of stadials and interstadials for the period 23,000 to 11,500 ice-core years BP, based on marked oxygen isotope variations in the GRIP ice core. Greenland Interstadial 1 (GI-1), which is broadly correlative with the Lateglacial or Bølling-Allerød Interstadial, was subdivided into three warmer episodes GI-1a, GI-1c and GI-1e with intervening colder periods GI-1b and GI-1d.

It is important to stress that the INTIMATE Event Stratigraphy scheme was not proposed as the replacement for the existing regional stratigraphies, but rather as a standard against which to compare those stratigraphic schemes. Furthermore, it was intended that the Event Stratigraphy should serve as a basis for establishing the synchroneity (or asynchroneity) of comparable events or sequences of events throughout the North Atlantic region (Lowe et al., 2001).

The event stratigraphic scheme has recently been revised (Lowe et al., 2008) based upon the new Greenland Ice core record from NorthGRIP (NGRIP) and the associated Greenland Ice Core Chronology 2005 (GICC05) (Rasmussen et al., 2006). The ice-core based event stratigraphy has the advantage of being based on a continuous and annually resolved palaeoclimate archive, which provides an unprecedented level of precision and accuracy for determining the timing and duration of climate events during the LGIT (see further Lowe et al., 2008).

Table 2 Event stratigraphy for the Last Glacial-Interglacial Transition based on the NGRIP oxygen isotope stratigraphy presented on the GICC05 timescale (Rasmussen et al., 2006): age b2k is before 2000 AD with the maximum counting error (MCE) and conversion to cal BP (before 1950).

	age b2k	MCE	cal BP
Holocene			
	11,703	99	11,653
GS-1			
	12,896	138	12,846
GI-1a			
	13,099	143	13,049
GI-1b			
	13,311	149	13,261
GI-1c			
	13,954	165	13,904
GI-1d			
	14,075	169	14,025
GI-1e			
	14,692	186	14,642
GS-2			

The revised INTIMATE event stratigraphy for the LGIT in the North Atlantic region is presented in Table 2. The ages for the event boundaries are derived from the GICC05 timescale (Rasmussen et al., 2006) in years b2k (= before 2000 AD). Note that this ice-core-based time-scale is different from the calibrated ^{14}C-timescale given in cal BP (=before 1950 AD). In effect, there is an offset of 50 years between the two timescales which must be taken into account when comparing ice-core years to ^{14}C-dated events.

An additional basis for correlation in the North Atlantic region during the LGIT is provided by tephrochronology. This time period in geological history is marked by the frequent occurrence of volcanic eruptions, possibly related to the glacio-isostatic compensation since the last deglaciation, and both visible and microtephras form valuable time-parallel marked horizons in marine and terrestrial sediments, and also in the ice-core record (Turney et al., 2004; Alloway et al., 2007; Lowe et al., 2008).

Discussion: climate changes during the Last Glacial-Interglacial Transition

Although lithological and botanical evidence shows that marked environmental changes occurred during the Lateglacial, it is often difficult to relate these signals directly to climate. The AP (Arboreal Pollen) percentage was long considered as a direct temperature proxy. Based on the palynological records, in which the AP percentage increased during the course of the Bølling-Allerød Interstadial, it was concluded that the warmest part of the Lateglacial occurred towards the end of the Allerød interstadial, just before the onset of the Younger Dryas Stadial. Evidence from fossil beetles (Coleoptera), however, suggested a different scenario, with the warmest phase occurring early in the Lateglacial (Coope, 1970; Coope et al., 1971). This interpretation was subsequently confirmed by data from the Greenland ice-core record, notably GRIP (Johnsen et al., 1992) and GISP2 (Grootes et al., 1993). Hence, the long-standing interpretation of Lateglacial climate and vegetational development appeared to be in error: the warmest phase did not occur during the Allerød, but rather during the Bølling when the extent of arboreal vegetation was limited. However, the timing of the changes in vegetation composition appears to be synchronous with the climate changes recorded in the oxygen isotope records in both ice-cores and calcareous lake deposits, for example in the Swiss Alps (Lotter et al., 1992) and in Central North America (Yu and Eicher, 1998). This points to a common temperature trend during the LGIT throughout the Atlantic region. Ammann et al. (2000), and Birks et al. (2000) found that at the beginning and end of the Younger Dryas in Ger-

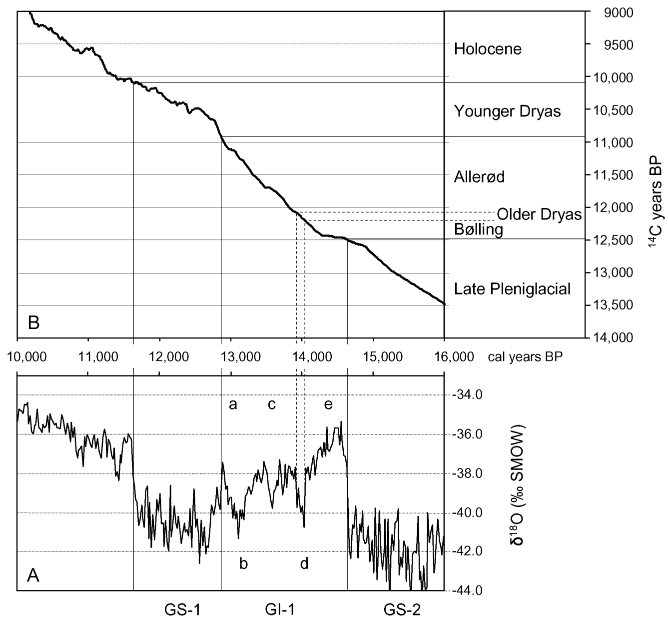

Figure 1 Correlation between the event stratigraphy for the Last Glacial-Interglacial Transition (A) after Lowe et al. (2008) plotted on a time scale in ice-layer counts BP (=1950 AD or b2k minus 50 years) and the classic Lateglacial stratigraphy of NW Europe (B) plotted on a ^{14}C time scale. The correlation has been made using the INTCAL04 calibration curve (Reimer et al., 2004).

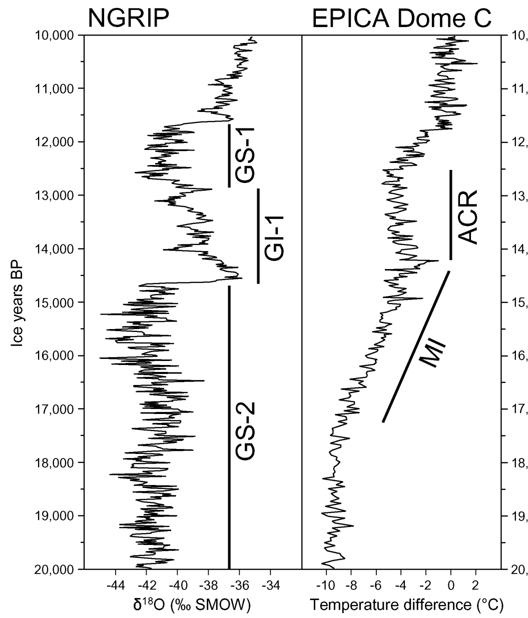

Figure 2 Comparison of the Greenland NGRIP oxygen isotope record (after Rasmussen et al., 2006 and Lowe et al., 2008) and the inferred temperature difference record from the Antarctic EPICA Dome C record (Jouzel et al., 2007). The Greenland Isotope events (GS-1, GI-1 and GS2) are clearly not coinciding with the Antarctic Cold Reversal (ACR) and Mystery Interval (MI).

many, Switzerland, and Norway, respectively, hardly any or no biotic lags occurred. This can also be deduced from figure 1, where the Greenland isotope events are compared with the classic Lateglacial stratigraphy for NW Europe. In this comparison, the ice core years (plotted in cal BP) are transferred to ^{14}C years BP using the INTCAL04 calibration dataset (Reimer et al., 2004). There is a remarkable similarity between the major zone boundaries and the transitions between GI-1, GS-1 and the Holocene, corresponding with, respectively, 12,500, 11,900, and 10,150 ^{14}C yrs BP as ^{14}C-dated in The Netherlands (see Figure 1 and above).

The causes behind the abrupt climate changes are still not completely resolved, although it is obvious that the changes in ocean circulation played a crucial role (Broecker, 1998). Furthermore, the interaction of the cryosphere and the ocean, in particularly the Atlantic (Bond et al., 1992), is believed to have been the major cause behind the rapid climate changes during the LGIT. The Younger Dryas (GS-1) was most likely caused by changes in Thermohaline Circulation in the North Atlantic as a result of fresh water forcing, while the start of the Holocene seems approximately to coincide with the onset of a ^{14}C plateau, implying an increased global ocean ventilation rate (Hughen et al., 2004; Björck, 2006).

The findings that warmings during glacial time in Antarctic ice cores roughly coincide with cold periods over the Greenland Summit, and vice versa, led to the hypothesis of a bi-polar seesaw climate pattern (Broecker, 1998). Meltwater Pulse 1a (a major influx into the world's oceans of meltwaters from wasting ice sheets) seems to coincide with the onset of GI-1 warming in the N-Atlantic at around 14.7 ka, and probably originated from the Antarctic Ice (Weaver et al., 2003). The occurrence of the Heinrich 1 event (massive iceberg discharge into the North Atlantic) at around 17.5 ka seemed to be the major cause in large changes in the meridional overturning registered in marine cores. This coincides with the onset of deglacial warming in the Antarctic, which has been referred to as the 'Mystery Interval' (Denton et al., 2006).

As the term 'Mystery Interval' indicates, there are substantial issues that remain to be solved. Clear differences can be observed in the registration of the climate signal between the southern and northern Hemispheres (see Figure 2). The Antarctic Cold Reversal (ACR) began more than 1000 years before the onset of the Younger Dryas in the north, but not in direct 'anti-phase' with the Bølling-Allerød (GI-1) warming in the north (Björck, 2006). While laminated lake sequences (Litt et al., 2001) confirm the synchroneity of the climate events during the LGIT in Europe, the ^{14}C-dated laminated sequence from Lake Suigetsu in Japan (Nakagawa et al., 2003) points towards an offset in the Pacific region relative to both the Greenland and Antarctic ice- core records. Finally, in a recent paper, Firestone et al. (2007) presented new evidence for an extraterrestrial impact presumably causing the onset of the Younger Dryas. However, precise dating of the postulated impact is not very accurate and much more research is needed to confirm the occurrence of this event, and its possible impact on LGIT climate.

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References

Alloway, B. V., Lowe, D. J., Barrell, D. J. A., Newnham, R. M., Almond, P. C., Augustinus, P. C., Bertler, N. A. N., Carter, L., Litchfield, N. J., McGlone, M. S., Vandergoes, M. J., Williams, P. W., and NZ-INTIMATE Members, 2007, Towards a climate event stratigraphy for New Zealand over the past 30,000 years (NZ-INTIMATE Project): Journal of Quaternary Science, 22, pp. 9–35.

Ammann, B., Birks, H. J. B., Brooks, S., Eicher, U., von Grafenstein, U., Hofmann, W., Lehmdahl, G., Schwander, J., Tobolski, K., and Wick, L., 2000, Quantification of biotic responses to rapid climatic changes around the Younger Dryas—a synthesis: Palaeogeography, Palaeoclimatology, Palaeoecology, 159, pp. 313–347.

Birks, H. H., and Ammann, B., 2000, Two terrestrial records of rapid climatic change during the glacial-Holocene transition (14,000–9,000 calendar years B.P.) from Europe: PNAS, 97-4, pp. 1390–1394.

Björck, S., Walker, M. J. C., Cwynar, L. C., Johnsen, S., Knudsen, K. -L., Lowe, J. J., Wohlfarth, B., and INTIMATE Members, 1998, An event stratigraphy for the Last Termination in the North Atlantic region based on the Greenland ice-core record: a proposal by the INTIMATE group: Journal of Quaternary Science, 13, pp. 283–292.

Björck, S., 2006, Younger Dryas oscillation, global evidence. *In* S. A. Elias, (Ed.): Encyclopedia of Quaternary Science, Volume 3, pp. 1987–1994. Elsevier B.V., Oxford.

Bond, G., Heinrich, H., Broecker, W., Labeyrie, L., McManus, J., Andrews, J., Huon, S., Jantschik, R., Clasen, S., Simet, C., Tedesco, K., Klas, M., Bonani, G., and Ivy, S., 1992, Evidence for massive discharges of icebergs into the North Atlantic ocean during the last glacial: Nature, 360, pp. 245–249.

Broecker, W. S., 1998, Paleocean circulation during the last deglaciation: a bipolar seesaw?: Paleoceanography, 13, pp. 119–121.

Coope, G. R., 1970, Climatic interpretation of Late Weichselian coleoptera from the British Isles. Revue de Géographie Physique et de Géologie Dynamique, 12, 149–155.

Coope, G. R., Morgan, A., and Osborne, P. J., 1971, Fossil coleoptera as indicators of climatic fluctuations during the Last Glaciation in Britain: Palaeogeography, Palaeoecology, Palaeoclimatology, 10, 87–101.

De Klerk, P., 2004, Confusing concepts in Lateglacial stratigraphy and chronology: origin, consequences, conclusions (with special emphasis on the type locality Bøllingsø): Review of Palaeobotany and Palynology, 129(4), pp. 265–298.

Denton, G. H., Broecker, W. S., and Alley, R. B., 2006, The mystery interval 17.5 to 14.5 kyrs ago: PAGES Newslettter, 14(2), pp. 14–16.

Firbas, F., 1954, Die Synchronisierung der mitteleuropäischen Pollendiagramme: Danmarks Geologiske Undersøgelse II 80, pp. 12–21.

Firestone, R. B., West, A., Kennett, J. P., Becker, L., Bunch, T. E., Revay, Z. S., Schultz, H., Belgya, T., Kennett, D. J., Erlandson, J. M., Dickenson, O. J., Goodyear, A. C., Harris, R. S., Howard, G. A., Kloosterman, J. B., Lechler, P., Mayewski, P. A., Montgomery, J., Poreda, R., Darrah, T., Que Hee, S. S., Smith, A. R., Stich, A., Topping, W., Wittke, J. H., and Wolbach W.S., 2007, Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling: PNAS, 104, pp. 16016–16021.

Grootes, P. M., Stuiver, M., White, J. W. C., Johnsen, S., and Jouzel, J., 1993, Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores: Nature, 366, pp. 552–554.

Hartz, N., and Milthers, V., 1901, Det senglaciale ler i Allerød Teglværksgrav: Meddelelser fra Dansk Geologisk Forening, 2, pp. 31–60.

Hoek, W.Z., 2001, Vegetation response to the ~ 14.7 and ~ 11.5 ka cal. BP climate transitions: is vegetation lagging climate?: Global and Planetary Change, 30, pp. 103–115.

Hughen, K., Lehman , S., Southon, J., Overpeck, J., Marchal, O., Herring, C., and Turnbull, J., 2004, 14C activity and global carbon cycle changes over the past 50,000 years: Science, 303, pp. 202–207.

Iversen, J., 1942, En pollenanalytisk Tidsfaestelse af Ferskvandslagene ved Nørre Lyngby: Meddelelser fra Dansk Geologisk Forening, 10, pp. 130–151.

Jessen, K., 1935, The composition of the forests in Northern Europe in epipalaeolithic time: Biologiske Meddelser, 12(1), 64 pp.

Johnsen, S. J., Clausen, H. B., Dansgaard, W., Fuhrer, K., Gundestrup, N., Hammer, C. U., Iversen, P., Jouzel, J., Stauffer, B., and Steffensen, J. -P., 1992, Irregular glacial interstadials recorded in a new Greenland ice core: Nature, 359, pp. 311–313.

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J., Barnola, J.M., Chappellaz, J., Fischer, H., Gallet, J. C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schilt, A., Schwander, J., Selmo, E., Souchez, R., Spahni, R., Stauffer, B., Steffensen, J. P., Stenni, B., Stocker, T. F., Tison, J. L., Werner, M., and Wolff, E. W., 2007, Orbital and Millennial Antarctic Climate Variability over the Past 800,000 Years: Science, 317, pp. 793–797.

Litt, T., Brauer, A., Goslar, T., Merkt, J., Balaga, K., Müller, H., Ralska-Jasiewiczowa, M., Stebich, M., and Negendank, J. F. W., 2001, Correlation and synchronisation of Lateglacial continental sequences in northern central Europe based on annually-laminated lacustrine sediments: Quaternary Science Reviews, 20, pp. 1233–1250.

Lotter, A. F., Eicher, U., Birks, H. J. B., and Siegenthaler, U., 1992, Lateglacial climatic oscillations as recorded in Swiss lake sediments: Journal of Quaternary Science, 7, pp. 187–204.

Lowe, J. J., Hoek, W. Z., and INTIMATE group, 2001, Inter-regional correlation of palaeoclimatic records for the Last Glacial-Interglacial Transition: a protocol for improved precision recommended by the INTIMATE project group: Quaternary Science Reviews, 20, pp. 1175–1187.

Lowe, J. J., Rasmussen, S. O., Björck, S., Hoek, W. Z., Steffensen, J. P., Walker, M. J. C., Yu, Z., and INTIMATE group, 2008, Precise dating and correlation of events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group: Quaternary Science Reviews, 27, in press, doi:10.1016/j.quascirev.2007.09.016.

Mangerud J., Andersen, S. T., Berglund, B. E., and Donner, J. J., 1974, Quaternary stratigraphy of Norden, a proposal for terminology and classification: Boreas, 3, pp. 109–128.

Nakagawa, T., Kitagawa, H., Yasuda, Y., Terasov, P. E., Nishida, K., Gotanda, K., Sawai, Y., and Yangtze River Civilisation Program Members 2003, Asynchronous climate changes in the North Atlantic and Japan during the Last termination: Science, 299, pp. 688–691.

Rasmussen, S. O., Andersen, K. K., Svensson, A. M., Steffensen, J. -P., Vinther, B., Clausen, H. B., Siggaard-Andersen, M. L., Johnsen, S. J., Larsen, L. B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M., and Ruth, U., 2006, A new Greenland ice core chronology for the last glacial termination: Journal of Geophysical Research, 111, D06102, doi:10.1029/2005JD006079.

Reimer, P. J., Baille, M. G. L., Bard, E., Bayliss, A., Warren, B. J., Chanda, B. J. H., Blackwell, P. G., Buck, C. E., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Hogg, A. G., Hughen, K. A., Kromer, B., McCormac, G., Manning, S., Ramsey, C. B., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver, M., Talamo, S., Taylor, F. W., van der Plicht, J., and Weyhenmeyer, C. E., 2004, IntCal04 terrestrial radiocarbon age calibration, 0-26 cal kyr BP. Radiocarbon, 46, pp. 1029–1058.

Turney, C. S. M., Lowe, J. J., Davies, S. M., Hall, V., Lowe, D., Wastegård, S., Hoek, W. Z., Alloway, B., SCOTAV, and INTIMATE members, 2004, Tephrochronology of Last Termination sequences in Europe: a protocol for improved analytical precision and robust correlation procedures (a joint SCOTAV-INTIMATE proposal): Journal of Quaternary Science, 19, pp. 111–120.

Van der Hammen, T., 1949, De Allerød-oscillatie in Nederland, pollenanalytisch onderzoek van een laatglaciale meerafzetting in Drente, I & II, Koninklijke Nederlandse Academie van Wetenschappen Proceedings, 52, pp. 69–75 and 169–176.

Van der Hammen, T., 1951, Late-Glacial flora and periglacial phenomena in The Netherlands. PhD-thesis, Leiden, Leidse Geologische Mededelingen, 17, pp. 71–183.

Walker, M. J. C., Björck, S., Lowe, J. J., Cwynar, L. C., Johnsen, S. J., Knudsen, K. L., Wohlfarth, B., and INTIMATE Group, 1999, Isotopic 'events' in the GRIP ice core: a stratotype for the Late Pleistocene: Quaternary Science Reviews, 18, pp. 1143–1150.

Weaver, A. J., Saenko, O. A., Clark, P. U., and Mitrovica, J. X., 2003, Meltwater Pulse 1a from Antarctica as a Trigger of the Bølling–Allerød Warm Interval: Science, 299, 1709–1713.

Yu, Z., and Eicher, U., 1998, Abrupt Climate Oscillations During the Last Deglaciation in Central North America: Science, 282, pp. 2235–2238.

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by James G. Ogg[1] and Brad Pillans[2]

Establishing Quaternary as a formal international Period/System

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Despite being the most widely used unit in field mapping and having the greatest number of active researchers, the interval known as Quaternary is unique among the chronostratigraphic subdivisions of the Geological Time Scale (GTS) in having the most controversial definition and rank. After more than 100 years of debate, the base of the Quaternary is now widely recognized at ~2.6 Ma, marking a dramatic and so-far irreversible shift to the ice-age-dominated world of oscillating glacial advances over the northern continents. In 2007, both INQUA and ICS proposed that the Quaternary be established as a System of the Cenozoic Erathem, with its base defined by the GSSP of the Gelasian Stage. To maintain strict hierarchy in the GTS, it is proposed that the base of the Pleistocene Series be lowered to coincide with the Gelasian Stage GSSP at ~2.6 Ma.

Overview

The Cenozoic Era currently has two ratified international periods/systems defined by *global boundary stratotype sections and points* (GSSPs). The Paleogene Period/System was ratified in 1991 by the *International Union of Geological Sciences* (IUGS) upon the acceptance of the basal-Danian GSSP. The Neogene Period/System was ratified in 1996. The interval known as Quaternary had been left undefined and without rank since 1983 upon the acceptance by IUGS of the GSSP that currently defines the base of the Pleistocene Series (base of Calabrian Stage in Mediterranean usage, ca. 1.8 Ma).

The *International Union of Quaternary Research* (INQUA; under the International Council for Science) and its component national members have unanimously agreed that the “Quaternary Period spans the last 2.6 million years of Earth's history” (*www.inqua.tcd.ie*). It begins with the first widespread continental glaciation that created deposits historically mapped as “Quaternary” and coincides with the base of the Gelasian Stage. In 2005, the International Commission of Stratigraphy (ICS) unanimously approved recognition of the Quaternary as a formal chronostratigraphic unit with its base at the Gelasian GSSP.

The ICS submitted a resolution in May 2007 to IUGS for the definition and associated rank of the Quaternary. In accordance with the IUGS requirements that establishing the Quaternary must not violate the hierarchical nature of the geological time scale and that the formalization of Quaternary must be in collaboration with INQUA, then it was necessary to simultaneously transfer the Gelasian Stage to the Pleistocene Series.

ICS recommends that IUGS establish the Quaternary as the uppermost System of the Cenozoic Erathem consistent with the usage of Quaternary by *International Union for Quaternary Research* (INQUA):

1) The Quaternary is a full formal chronostratigraphic unit, the appropriate status for which is the System. The underlying System is the Neogene.
2) The base of the Quaternary is placed at the current base of GSSP Gelasian Stage (currently in the Pliocene) at the base of Marine Isotope Stage (MIS) 103, which has been calibrated to an age of ~2.6 Ma.
3) The base of the Pleistocene Series is lowered to coincide with that of the Quaternary System boundary (= Gelasian Stage GSSP).
4) The GSSP at Vrica, Italy (the former Plio-Pleistocene boundary), is retained as the base of the Calabrian Stage, the second stage of the revised Pleistocene Series.

In May 2007, the IUGS indicated that defining the Quaternary as a formal chronostratigraphic unit with a GSSP will be discussed further at the 2008 International Geological Congress (IGC).

In August 2007, INQUA, in unprecedented *unanimous* votes within both the assembly of its component national members and in a General Assembly (ca. 600 members), agreed on establishing the Quaternary as a system with its base coinciding with the present Gelasian GSSP. Therefore, the vast majority of active geoscientists in all nations that are engaged on Quaternary studies have achieved a milestone in defining the onset of this period.

The establishment of the Quaternary as a Period/System has a few controversial aspects, which is one reason that it has been without rank or accepted definition since 1983. However, INQUA and the majority of ICS considers that establishing the Quaternary as a formal period/system is consistent with its widespread usage in relation to continental deposits and establishes it as a unique interval of Earth's history in climates and human evolution.

The onset of the ice ages and beginning of the Quaternary

Despite being the most widely used unit in field mapping and having the greatest number of active researchers, the interval known as *Quaternary* is unique among the chronostratigraphic subdivisions in having the most controversial definition and rank (Figure 1). The convoluted history and divergent concepts of Quaternary usage is fraught with opinionated debate, beginning with the early International Geological Congresses which considered relegating *Quaternary* to be an un-ranked synonym for a vaguely defined *Pleistocene epoch* (1894) or replaced with a “Modern” period (1900). Many field workers had simply assigned a vague “Quaternary” to relatively unconsolidated material that overlies more lithified continental deposits.

The common association of *Quaternary* with the “Ice Ages” created another problem, because the onset of these continental glaciations is now known, from ice-rafted debris in the Greenland Sea, to have begun much earlier, in the mid-Paleogene, around 44 Ma (Tripati et al., 2008).

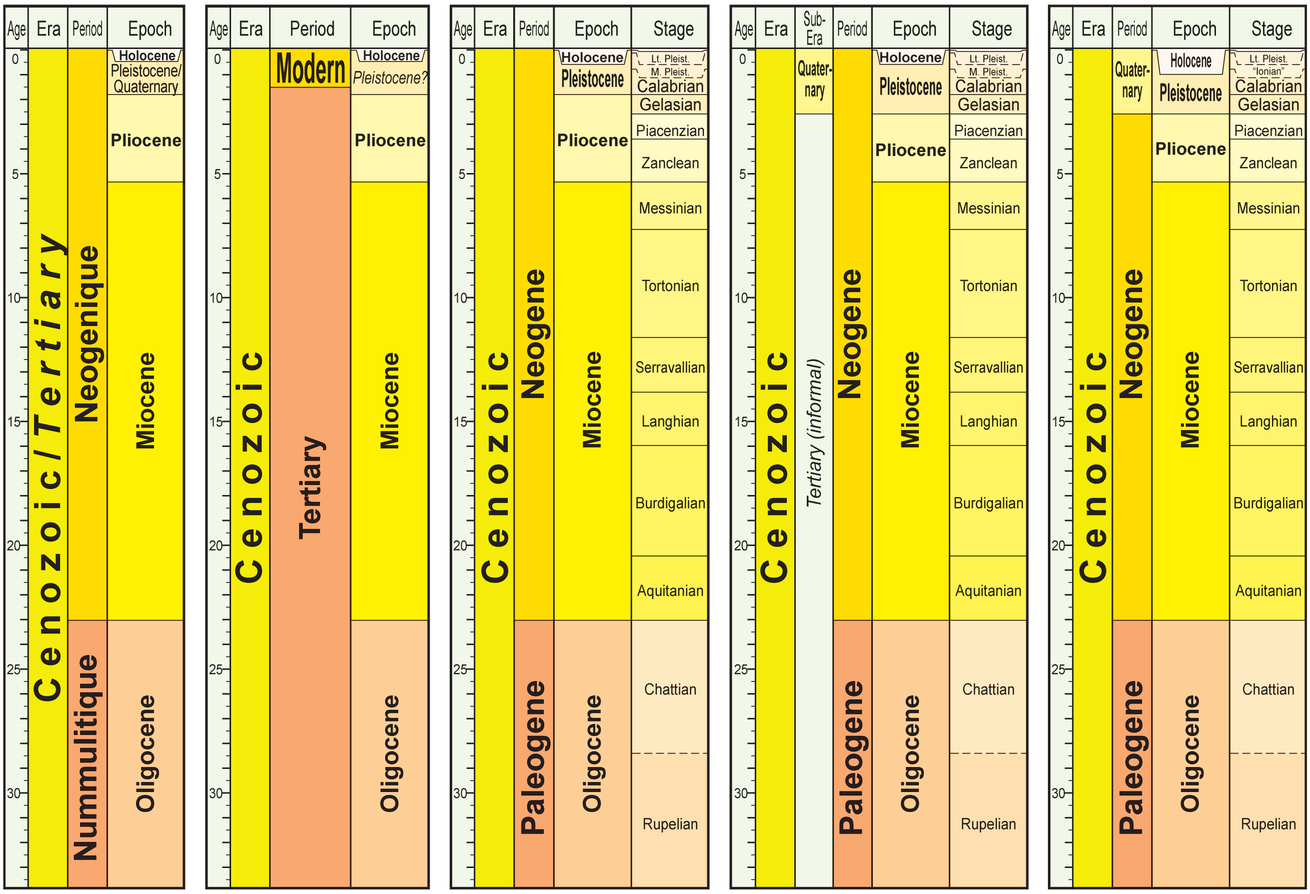


Figure 1 Selected versions of Cenozoic subdivisions and nomenclature for Oligocene-Holocene interval.

(a) 1894–The forerunner to the ICS proposed that the Cenozoic/Tertiary Era be subdivided into *Nummulitique* (Paleocene-Eocene-Oligocene) and *Neogenique* (Miocene-Pliocene-Pleistocene-Holocene); with *Quaternary* or *Diluvium* as "general synonyms" for Pleistocene (Renevier et al., 1894). The Sixth International Geological Congress (IGC) published the document, but no formal decision was made.

(b) 1900–A proposal was submitted to the Eighth IGC to subdivide Cenozoic into Tertiary and Modern periods, with *Primary* and *Secondary* retained as synonyms for the Paleozoic and Mesozoic. No formal decision was made.

(c) 1996–IUGS had ratified the Paleogene and Neogene as period/systems. During the IUGS acceptance of the Pleistocene in 1985, the Quaternary had been left without rank. INQUA defined the Quaternary as spanning the past 2.6 myr. This was the status indicated in *Geologic Time Scale* 2004.

(d) 2005–The ICS proposes to IUGS to instate the Quaternary as a sub-era beginning with the first major "Ice Age"–the 2.6 Ma age of the earliest major continental glaciation obtained by INQUA. Under that proposal, the Tertiary would be an informal sub-era spanning the lower 95% of the Cenozoic. This proposal, which summarized in Aubry et al. (2005), is rejected by IUGS.

(e) 2007–The ICS and INQUA jointly propose to IUGS to insert the Quaternary as a period/system using the 2.6-myr definition (base of Gelasian) voted unanimously by INQUA in 2007. To retain a hierarchical scale, the Gelasian stage is shifted to the Pleistocene. This proposal of ICS and INQUA is pending for the International Geological Congress in 2008.

In 1983, in a controversial decision, the base-Pleistocene GSSP was ratified at Vrica, Italy, near the top of the Olduvai magnetic subchron, but the decision "*was isolated from other more or less related problems, such as ... status of the Quaternary*" (Aguirre and Pasini, 1985). The Gelasian Stage was later created (ratified in 1996 at the 30th International Geological Congress, Beijing) to fill the "gap" between this GSSP and the "traditional" span of the Piacenzian Stage of the Pliocene Series (Rio et al., 1998). However, when the base-Pleistocene GSSP was established, the timing of the initial major glaciation of the Northern Hemisphere was not well understood.

The base of the Quaternary has now been established from the recognition and precise dating of glacial-driven major oxygen-isotope excursions, of pronounced eustatic lowstands on continental shelves caused by the formation of massive glacial sheets, of the onset of the main loess deposition in China, of the lowest till deposits in central USA, and of other traditional "Quaternary" deposits (Figure 2). The evidence accumulated during the past two decades is uncontroversial—at approximately 2.6 or 2.7 Ma there was a dramatic and so-far irreversible shift to the ice-age-dominated world of oscillating glacial advances over the northern continents. This earliest major glaciation produced a major global sea-level lowstand at 2.7 Ma (major sequence boundary "Ge1" of Hardenbol et al., 1998) that coincides with cold oxygen-isotope stage 110, and deposited the Atlanta glacial till in Missouri (e.g., Balco et al., 2005) among other widespread glacial evidence. There was also a surge in ice-rafted debris in the northern oceans, and the establishment of the modern patterns of deep-sea circulation (e.g., Haug et al., 2005; Bartoli et al., 2005). The conditions that led to this initial Ice Age probably included blocking of exchange of tropical Atlantic-Pacific waters by the formation of the Isthmus of Panama, among other tectonic and atmospheric-oceanic factors. A side effect was the emergence of bipedal humanoids; and this new generation of Lucy and her brothers has been called "Children of the Ice Age" (e.g., Stanley, 1996).

The base of the current Gelasian Stage was placed at a slightly younger level (warm interval MIS 103; age 2.59 Ma), but its association with the magnetic reversal at the onset of the Matuyama reversed-polarity Chron enables an unambiguous and precise global marker. Therefore, for expediency and unambiguous high-precision correlation between continental and oceanic deposits, the Quaternary System is being defined with this established Gelasian GSSP.

Further details on the base of the Quaternary are given by Head et al. (in this *Episodes* volume).

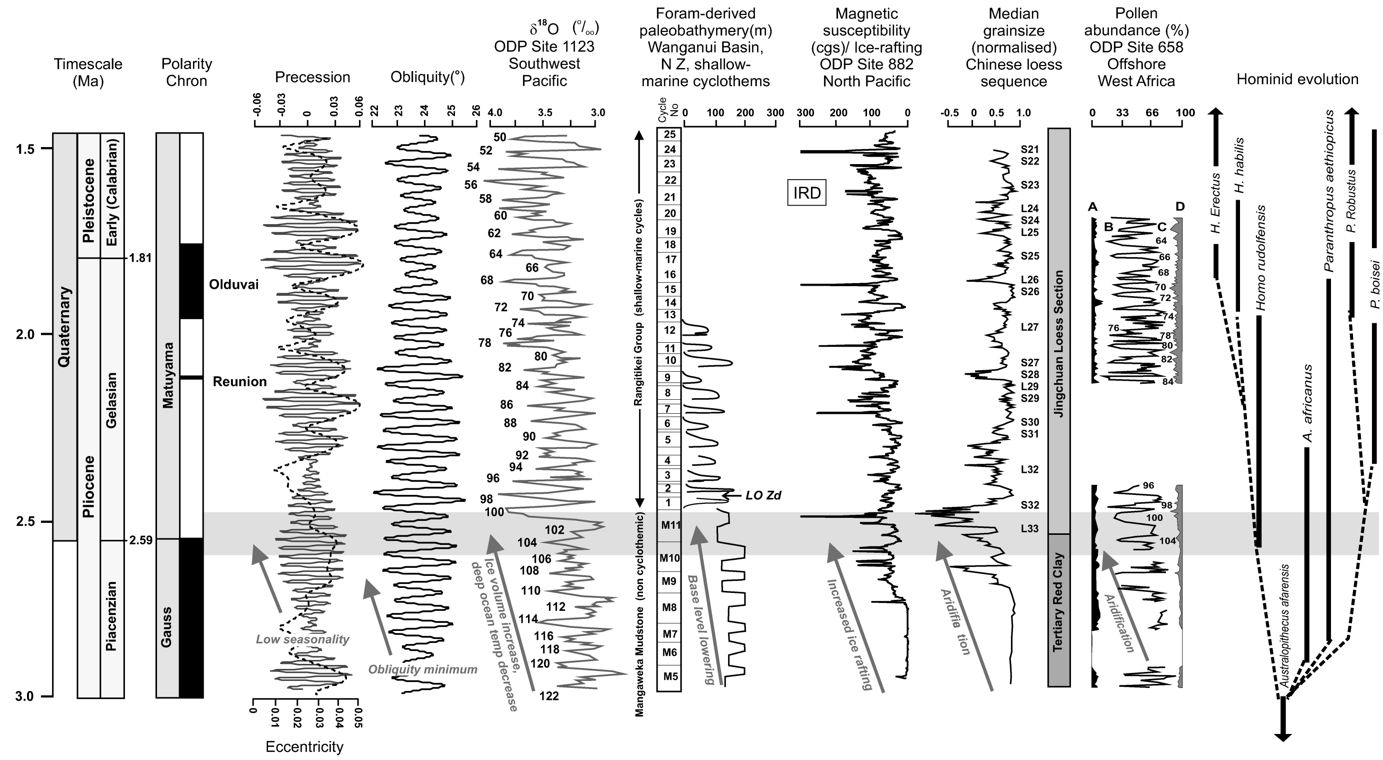


Figure 2** Temporal and latitudinal relations between orbital forcing and Earth's Late Pliocene-Early Pleistocene climate (3.0-1.5 Ma) as recorded by a high-resolution deep ocean $\delta^{18}O$ ice volume record from Southwestern Pacific ODP site 1123, glacio-eustatic cyclothems of Wanganui Basin New Zealand, ice rafting as recorded by magnetic susceptibility at North Pacific ODP site 882, and a median grainsize profile of the Jingchuan Loess Section, North central China Loess Plataeu. LO Zd denotes first appearance in North Island of New Zealand stratigraphic record of the subantarctic scallop* **Zygochlamys delicatula** *during glacial periods, traditionally marking the Plio-Pleistocene boundary in New Zealand. Pollen summary diagram from ODP 658, offshore West Africa shows progressive aridification of Northwest Africa between 2.8 and 2.4 Ma, as (B) sahel-savanna grassland and open forest elements are replaced by drier (C) saharan desert vegetation. Subordinate vegetation assemblages (A) and (D) represent a tropical coastal forest and "Mediterranean" (trade wind) elements, respectively. Note well-developed 40 ka glacial-interglacial modulation of the sahel-savanna boundary following 2.6 Ma. A step-like 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 (Australopithecus afarensis***). From Pillans and Naish (2004).*

Lowering of the Pleistocene base

Thus, the onset of the Quaternary is nearly 800,000 years prior to the placement of the base-Pleistocene GSSP (ca. 1.8 Ma) at the level when certain cooler-water marine fauna enter the Mediterranean (Aguirre and Pasini, 1985). When this base-Pleistocene GSSP was established in 1983, there was inconclusive global evidence about the age of the earliest Quaternary glaciations. Therefore, to rectify the offset of Quaternary (as used by INQUA and its constituent international committees) and the 1983-version of the Pleistocene Epoch/Series, the ICS and INQUA agreed that the Gelasian Stage should be transferred to the Pleistocene, thereby enabling a Quaternary Period/System to be established within the Cenozoic (Figure 3). This also brings the lowered Pleistocene into better accord with the 1948 decision by the International Geological Congress Council that the Pleistocene should include the *Villafranchian* regional continental stage of which nearly half is currently in the late Pliocene (King and Oakley, 1949).

Neogene and Tertiary

The period/system that precedes the Quaternary is the internationally ratified Neogene. The original "Neogen ("new", "clan/birth") Stufe" of Moritz Hörnes was introduced in 1853/1864 to differentiate the younger molluscan fauna of the Vienna Basin from those of the Eocene (*sensu* Lyell, 1833). According to this division of the Molasse Group, the Neogene strata also included the "*Knochen-Höhlen und der Löss*" or glacial-derived deposits that are typical of "*Quaternary*" (see extended discussion by Lourens et al., 2004, and by Walsh, in press). Usage of "Neogene" by marine stratigraphers customarily includes the full suite of Miocene through Holocene epochs.

It had been recommended by Aubry et al. (2005) to establish separate Cenozoic divisions for oceanic and for continental deposits. In their scheme, the international Neogene and Paleogene periods/systems would have a parallel continental-based "sub-era" classification of the Quaternary (with its base at ca. 2.6 Ma; and offset from the marine-based Pleistocene definition) and a lengthy informal "*Tertiary*". This proposed duality, which would allow land-based and marine-based earth scientists to retain their own traditional schemes, was accepted by ICS in 2005 (12 Yes, 5 No = 70% Yes). However, the IUGS rejected this dichotomy proposal for two reasons. First, the IUGS was reluctant to establish a new chronostratigraphic unit ("sub-era"), and second, they ruled that any chronostratigraphic scale (hence, usage of Quaternary) must be hierarchical – the base of a higher-ranked unit must coincide with bases of all lower-ranked units, such as series/epochs. IUGS also emphasized that ICS must work with INQUA on an acceptable usage of Quaternary. The Neogene and Paleogene are ratified international periods defined by GSSPs, and INQUA was unwavering in its scientific definition of Quaternary and request that it be a period in Earth's history. Therefore, the preferred solution (82% Yes by ICS) was to simultaneously insert the Quaternary as a period/system that truncated the upper Neogene and to adjust the lower boundary of the Pleistocene Epoch/Series to coincide with this new Quaternary Period/System.

The term "Tertiary" is an informal grouping for the Neogene and Paleogene periods, and encompasses over 95% of the Cenozoic. As

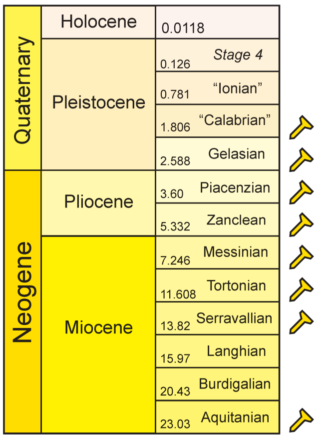
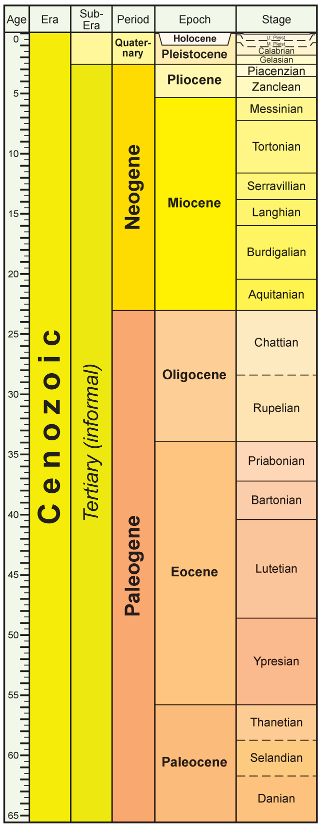


Figure 3 The proposed subdivisions of Neogene and Quaternary. The golden spikes are ratified global boundary stratotype sections and points (GSSPs). The uppermost Stage 4 of the Pleistocene will potentially be named **Tarantian**, *after the equivalent Mediterranean regional stage. The GSSP of the current Pliocene/Pleistocene boundary at ca. 1.8 Ma will be retained as the GSSP for the Calabrian Stage.*



such, it is much too broad to be a useful subdivision of the Cenozoic, unless stratigraphic evidence does not allow placement of a unit or event into the international-defined Neogene or Paleogene systems.

Acknowledgements

Portions of this review were extracted from the joint ICS-IUGS-INQUA task group report on Quaternary (2005), the ICS submission to IUGS requesting ratification of Quaternary as a Period (2007), extracts from historical documents in a presentation by Gian Battista Vai (2006), and from chapters and contributions to the ICS booklet “A Concise Geologic Time Scale” (Ogg et al, coordinators; 2008).

References

Aguirre, E., and Pasini, G., 1985, The Pliocene-Pleistocene Boundary: Episodes, v. 8, pp. 116–120.

Aubry, M-P., Berggren, W. A., Van Couvering, J., McGowran, B., Pillans, B., and Hilgen, F., 2005. Quaternary: status, rank, definition, survival: Episodes, v. 28, pp. 118–120.

Balco, G, Rovey II, C. W., and Stone, J. O. H., 2005. The first glacial maximum in North America: Science, v. 307, p. 222.

Bartoli G, Sarnthein M, Weinelt M, Erlenkeuser, H., Garbe-Schonberg, D., and Lea, D.W., 2005. Final closure of Panama and the onset of northern hemisphere glaciation: Earth and Planetary Science Letters, v. 237, pp. 33–44.

Berggren, W.A., 1998. The Cenozoic Era: Lyellian (chrono)stratigraphy and nomenclatural reform at the millennium, *in:* Blundell, D. J. and Scott, A. C. (editors), The Past is the Key to the Present: Geological Society, London, Special Publications, 143: 111–132.

Berggren, W.A., 2007. Status of the hierarchical subdivision of higher order marine Cenozoic chronostratigraphic units:Stratigraphy, v. 4, pp. 99–108.

Elias, S. A., 2007, Encyclopedia of Quaternary Science (4 volumes): Amsterdam, Elsevier.

Gibbard, P. L., Smith, A. G., Zalasiewicz, J. A., Barry, T. L., Cantrill, D., Coe, A. L., Cope, J. C. W., Gale, A. S., Gregory, F. J., Powell, J. H., Rawson, P. F., Stone, P. & Waters, C. N. 2005, What status for the Quaternary?: Boreas, v. 34, pp. 1– 6.

Hardenbol, J., Thierry, J., Farley, M. B., Jacquin, Th., de Graciansky, P.-C., and Vail, P. R. (with numerous contributors), 1998. Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins, *in*: Mesozoic-Cenozoic Sequence Stratigraphy of European Basins (edited by de Graciansky, P.-C., Hardenbol, J., Jacquin, Th., and Vail, P.R.), SEPM Special Publication (Tulsa), 60: 3–13, 763–781, and chart supplements.

Haug, G. H., Ganopolski, A., Sigman, D. M., Rosell-Mele, A., Swann, G. E. A., Tiedemann, R., Jaccard, S. L., Bollmann, J., Maslin, M. A., Leng, M.J., and Eglinton, G., 2005, North Pacific seasonality and the glaciation of North America 2.7 million years ago: Nature, v. 33, pp. 821–825.

King, W. B. R., and Oakley, K. P.,1949, Definition of the Pliocene-Pleistocene boundary: Nature, v. 163, p. 186

Lourens, L., Hilgen, F., Shackleton, N. J., Laskar, J., and Wilson, D, 2004, The Neogene Period, *in* Gradstein, F. M., Ogg, J. G., and Smith, A. G., eds, Geologic Time Scale 2004: Cambridge University Press, pp. 409–440.

Ogg, J., 2004, Introduction to concepts and proposed standardization of the term Quaternary: Episodes, v. 27, no. 2, pp. 125–126.

Pillans, B., 2004, Proposal to redefine the Quaternary: Episodes, v. 27, no.2, p. 127.

Pillans, B., and Naish, T., 2004, Defining the Quaternary: Quaternary Science Reviews, v. 23, pp. 2271–2282.

Renevier, E., 1894 (printed in 1897). Chronographe géologique: seconde édition du Tableau des terrains sédimentaires formés pendant les époques de la phase organique du globe terrestre. Compte-Rendu de la sexième session, Congrès Géologique International (Août, 1894, Zurich), printed by Georges Bridel and Co, Lausanne, in March, 1897, pp. 522–695.

Rio, D., Sprovieri, R., Castradori, D. and Di Stephano, E., 1998, The Gelasian Stage (Upper Pliocene): A new unit of the global standard chronostratigraphic scale: Episodes, v. 21, pp. 82–87.

Stanley, S.M., 1996, Children of the Ice Age: How a Global Catastrophe Allowed Humans to Evolve: Harmony publishers: 278 pp.

Tripati, A. K., Eagle, R. A., Morton, A., Dowdeswell, J. A., Atkinson, K. L., Bahe, Y., Dawber, C. F., Khadun, E., Shaw, R. M. H., Shorttle, O. and Thanabalasundaram, L., 2008, Evidence for glaciation in the Northern Hemisphere back to 44 Ma from ice-rafted debris in the Greenland Sea: Earth and Planetary Science Letters, v. 265, pp. 112–122.

Walsh, S. L., in press, The Neogene: origin, adoption, evolution, and controversy: Earth-Science Reviews.

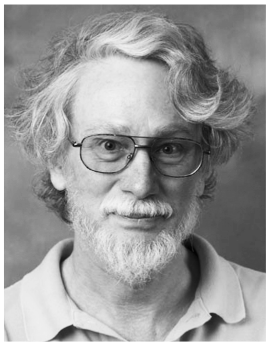
Selected On-Line References

Definition and geochronologic/chronostratigraphic rank of the term Quaternary, Recommendations by the Quaternary Task Group of ICS, IUGS and INQUA (2005): *www.stratigraphy.org/Q2.pdf*

Quaternary Subcommission: *www.quaternary.stratigraphy.org.uk,* Detailed interregional chart, status of Quaternary divisions, PDFs of major articles, and other information.

INQUA, the International Union for Quaternary Research (a full Science Union member of the International Council for Science): *www.inqua.tcd.ie*

James G. Ogg *has served as Secretary-General of the International Commission on Stratigraphy since 2000. As part of this role, he was a co-compiler of the Geologic Time Scale 2004 (Cambridge University Press, ca. 500 pages), and guided the development of the TimeScale Creator databases and visualization system (freely available at www.stratigraphy.org). James Ogg has served on nearly a dozen ocean drilling legs to explore the Mesozoic and early Cenozoic history of the Pacific, Atlantic and Indian Oceans.*



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by Martin J. Head[1], Philip Gibbard[2], and Amos Salvador[3]

The Quaternary: its character and definition

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The Quaternary is characterised by the development of widespread glaciations in mid-northern latitudes. As a chronostratigraphic term it has attracted vigorous debate. The Quaternary, as accepted by the International Union for Quaternary Research and proposed by the International Commission on Stratigraphy, begins at 2.6 Ma within a 2.8–2.4 Ma interval of profound change in Earth's climate system. The base of the Gelasian Stage at 2.588 Ma offers an existing global stratotype section and point to define the base-Quaternary, and this will necessitate lowering the base of the Pleistocene from its current 1.8 Ma to that of the Quaternary to maintain hierarchical order. This proposal recognises the distinctive qualities of the Quaternary, complies strictly with the hierarchical requirements of the geological time scale, and respects the historical and widespread current usage of the term Quaternary.

Introduction

The Quaternary is youngest in a fourfold chronostratigraphic subdivision proposed by Arduino in 1759 (Arduino, 1760). Although Arduino never actually used the term 'quaternario', referring instead to his 'fourth order' (Vaccari, 2006), the concept has been used for nearly 250 years. The current official status for the Quaternary is that of period/system with a base at 1.8 Ma (Cowie and Bassett, 1989; Remane, 2000; see Head, Gibbard and Salvador, this issue, Figure 1). Nonetheless, the Quaternary was omitted from the influential time scale of Gradstein et al. (2004), and this action immediately sparked vigorous debate about its nature, duration, and chronostratigraphic status. Indeed, the recent time scales of Gradstein et al. (2004, 2005), while not officially sanctioned by either the International Commission on Stratigraphy (ICS) or the International Union of Geological Sciences (IUGS), have stimulated productive discussions about the status of both the Quaternary and the Tertiary.

Recent proposals concerning the status of the Quaternary have included treating it as an informal chronostratigraphic unit, and formally as a sub-period, period, or sub-era (see Pillans and Naish, 2004; Gibbard et al., 2005; Aubry et al., 2005; Walsh, 2006; Bowen and Gibbard, 2007; and Pillans, 2007 for reviews; Figure 1). Objections to its treatment as an informal term include its precise and widespread use in the literature and among technological as well as scientific communities (Salvador, 2006a, b). Claims based on historical interpretation that the Neogene Period extends to the present day, thereby rendering the term Quaternary superfluous (e.g., Berggren, 1998; Lourens et al., 2005), have been refuted (Walsh, 2006, in press). Proposals for both sub-era and sub-period status deny the Quaternary its ubiquitous usage, and fail to respect the hierarchical nature of the stratigraphic time scale, when adopting a 2.6 Ma inception for the Quaternary.

After widely polling its constituents, the International Union for Quaternary Research (INQUA) in March 2006 notified the ICS of its requirements: the Quaternary to be of period status with its base at the GSSP of the Gelasian Stage (2.6 Ma), and that the base of the Pleistocene should also be lowered from its current 1.8 Ma to coincide with the base of the Quaternary. In May 2007, the ICS

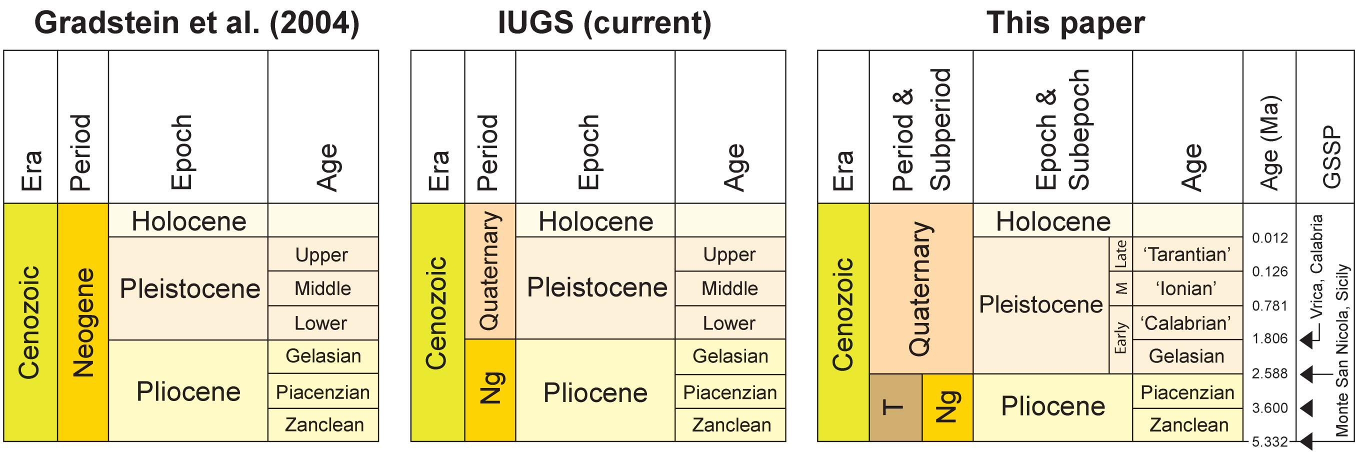

***Figure 1** Comparison of late Cenozoic time scales. The Gradstein et al. (2004) time scale in which the Quaternary and Tertiary are omitted. The current IUGS-sanctioned time scale showing the Quaternary in place (Remane, 2000). In our scheme, the Quaternary and Pleistocene are co-terminous with the base-Gelasian at 2.6 Ma, in agreement with the latest INQUA and ICS proposals. The Tertiary (T) is depicted as a period/system following the proposal of Head, Gibbard and Salvador (this issue). Stage names and boundary ages are from the ICS website in January 2008, with the provisional Calabrian and Ionian stages following Cita et al. (2006) and the provisional Tarantian Stage following Cita (this issue, and references therein). Presently defined GSSPs are indicated by black triangles. Only those GSSPs mentioned in the text are labeled. Ng = Neogene. The illustrations are not scaled to geological time.*

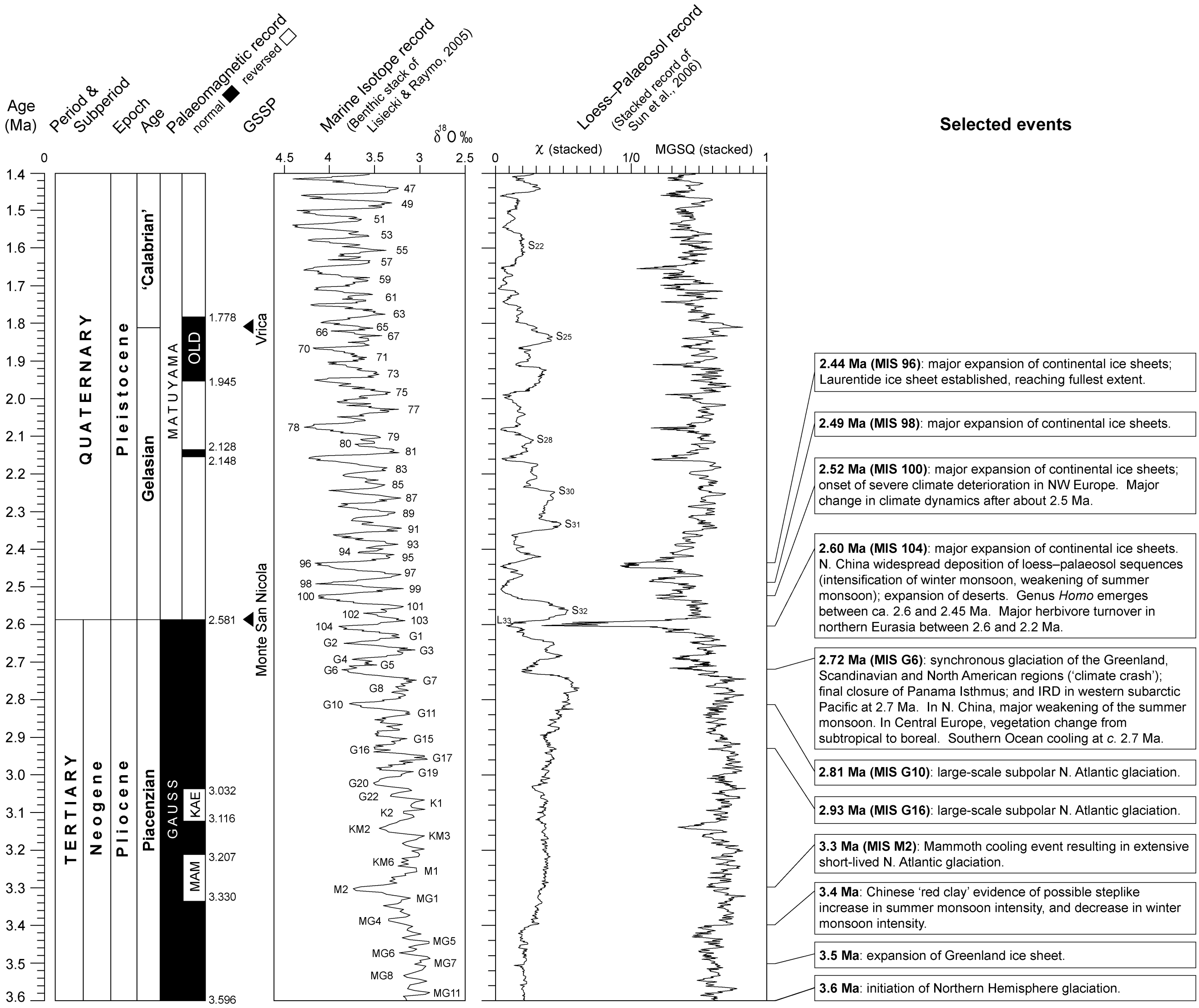

Figure 2 Selected events during the interval 1.4–3.6 Ma. Ages of magnetostratigraphic boundaries are from Lourens et al. (2005), although we note that Deino et al. (2006) gave an age of 2.610 Ma for the Gauss–Matuyama polarity boundary. The marine benthic foraminiferal $\delta^{18}O$ records and corresponding marine isotope stages are from Lisiecki and Raymo (2005), and the stacked loess–palaeosol records from the Chinese Loess Plateau (χ = magnetic susceptibility, MGSQ = mean size of quartz grains) are from Sun et al. (2006). The Tertiary is depicted as a period/system following the proposal of Head, Gibbard and Salvador (this issue). See text for explanation of events.

voted in favour of the INQUA proposal, but the International Union of Geological Sciences (IUGS), while approving the ICS's request to accept the Quaternary as a formal period, noted in correspondence to the ICS (in May 2007) that the base of the Pleistocene could not be moved until a 10-year moratorium had expired (in January 2009). This had come about because the IUGS (but not the ICS) had voted in January 1999 to uphold the base-Pleistocene GSSP after a joint Quaternary–Neogene task group reconsidering the level of the Pliocene–Pleistocene boundary was unable to reach a supermajority recommendation (Remane and Michelsen, 1998). The current IUGS decided to impose a 10-year moratorium on that earlier base-Pleistocene decision, thereby delaying further consideration of a definition for the Quaternary and associated shifting of the Gelasian Stage to the Pleistocene until January 2009. That brings us to the present situation.

A difficulty hindering all discussions about the definition and duration of the Quaternary has been the placement in 1985 of the Pliocene–Pleistocene boundary near the top of the Olduvai Subchron (Figure 2). This boundary has since been astronomically dated at 1.806 Ma (Lourens et al., 2005). It was defined by a Global Stratotype Section and Point (GSSP) at Vrica in Calabria, southern Italy in 1985 (Aguirre and Pasini, 1985; Cita, this issue), and reaffirmed by the IUGS in 1999 in the face of numerous objections (Gibbard et al., 2005; Bowen and Gibbard, 2007). Among these was that fundamental geological changes did not take place at or even near the chosen boundary. Indeed, some of the so-called 'northern guests', cold-tolerant migrants into the Mediterranean used as indicators of cooling at the boundary (Aguirre and Pasini, 1985), have since been found to have arrived in the Mediterranean earlier than 1.8 Ma (e.g., Aiello et al., 1996): an age of c. 2.5–2.7 Ma is more appropriate (e.g., Suc et al., 1997). It is now well documented that major cooling events in the Mediterranean occurred between about 2.8 and 2.5 Ma (e.g., Versteegh, 1997; Monegatti and Raffi, 2001; Roveri and Taviani, 2003), which coincides with the widely agreed base of the Quaternary.

There is now overwhelming support that the Quaternary be recognised as a full period/system extending from 2.6 Ma to the present day, and that the base of the Pleistocene be lowered to that of the Quaternary in order to maintain hierarchy (Ogg and Pillans, this issue). In elucidating this position, we summarise the progressive and fundamental changes to Earth's climate system that took place between about 2.8 and 2.4 Ma, and we review the profound affects of these changes on the oceans, atmosphere, landscape and biota (Figure 2). Finally, we discuss the practicalities of defining the base of the Quaternary.

Climate evolution

The onset of significant Northern Hemisphere glaciation at about 2.7 Ma occurs within the context of progressive Cenozoic cooling, and also a gradual increase in mean global ice volume between 3.6 and 2.4 Ma. This ice volume increase appears to be related to slow tectonic forcing, such as by mountain uplift or closure of ocean gateways (Mudelsee and Raymo, 2005). In addition, between 3.1 and 2.5 Ma, increased amplitude in the obliquity cycle would have led to repeated cold summers in the Northern Hemisphere, thus allowing the accumulation of winter ice. A threshold appears to have been crossed at around 2.7 Ma, providing the necessary conditions for significant Northern Hemisphere glaciation to occur (Berger and Loutre, 1991; Figure 2). Late summer sea-surface temperatures in the subarctic Pacific rose in response to increased stratification (even while winter temperatures cooled), and this may have provided moisture for ice accumulation in the Arctic regions (Haug et al., 2005). Increasing warmth and intensity of North Atlantic thermohaline circulation during the warm stages from 2.95 to 2.82 Ma might also have contributed significant moisture prior to major glaciation at around 2.8 Ma, which itself may have caused eustatic closure of the Panama Isthmus thereby leading to an increase in thermohaline circulation (Bartoli et al., 2005). A freshening of the Arctic Ocean by increased fluvial runoff will have facilitated the formation of Arctic sea-ice (Driscoll and Haug, 1998). Once established, the expansion of ice sheets in the Northern Hemisphere would have amplified long-term cooling through increased albedo. Moreover, the shape of climate cycles becomes asymmetrical (saw-toothed) after about 2.5 Ma, suggesting a major change in climate dynamics at this time (Lisiecki and Raymo, 2007).

Marine records

Ice-rafted debris (IRD) records of the Nordic Seas and North Atlantic show stepwise increase in large-scale glaciation between 3.5 and 2.4 Ma, beginning with an expansion of the Greenland ice sheet at 3.5 Ma, an extensive if short-lived glaciation at 3.3 Ma (Marine Isotope Stage [MIS] M2), and then progressive increases from 3.05 Ma (MIS G22) (Kleiven et al., 2002) including large-scale subpolar N. Atlantic glaciations at 2.93 (MIS G16) and 2.81 Ma (MIS G10) (Kleiven et al., 2002; Bartoli et al., 2005). Synchronous glaciation of the Greenland, Scandinavian and North American regions began at 2.72 Ma (MIS G6), an event that has been called the great 'climate crash' (Bartoli et al., 2005). Indeed, a sharp increase in IRD at 2.7 Ma in the western sub-arctic Pacific indicates a synchronous circum-arctic expansion of ice sheets, benthic foraminiferal records show a rapid reorganization of the North Atlantic thermohaline circulation at 2.72 Ma (Kleiven et al., 2002; Bartoli et al., 2005; Figure 2), and calcareous nannofossil evidence documents the final (eustatic) closure of the Panama Isthmus (Kameo and Sato, 2000).

A eustatic drop of c. 45 m has been estimated for the period 2.93–2.82 Ma (MIS G16–G10) and a further c. 45 m by 2.72 Ma (MIS G6) (Bartoli et al., 2005). Between 2.7 and 2.4 Ma, further significant ice-sheet expansions in the Nordic Seas and North Atlantic correspond to cold MIS 104, 100, 98 and 96 (Kleiven et al., 2002). This history of ice-sheet growth is mirrored in a major reorganization of the northern high-latitude marine faunal provinces (Bartoli et al., 2005).

Changes were not restricted to the Northern Hemisphere. In the Southern Ocean, the onset of water column stratification at 2.7 Ma mirrors that of the subarctic Pacific and was caused by global cooling, and such stratification might have trapped CO_2 in the abyssal depths of the world's ocean, providing a positive feedback for further cooling (Sigman et al., 2004). Synchronous peaks in ice-rafted debris (IRD) at 2.9–2.7 Ma off the Antarctic Peninsula and SE Greenland attest to this being a bipolar event (St. John, 2004).

Continental records

Ice sheet expansion occurred in Iceland during MIS G6 and especially G4 and onwards (Geirsdottir and Eiriksson, 1994; Kleiven et al., 2002), and the North American Laurentide ice sheet reached its fullest extent during its initial expansion at c. 2.4 Ma (the Atlanta till; Balco et al., 2005; Ehlers and Gibbard, this issue).

In northern China, the widespread deposition of loess–palaeosol sequences, accompanied by significant expansion of deserts, began abruptly at 2.6 Ma as a result of the intensification of the East-Asian winter monsoon and weakening of the summer monsoon (Ding et al., 2005). Since the altitude of the southern plateau of Tibet had not changed substantially since the mid-Pliocene, strong aridification associated with the onset of major loess–paleosol deposition at c. 2.6 Ma was largely brought about by Northern Hemisphere glaciation and the concomitant strengthening of the Siberian high-pressure cell (Ruddiman and Kutzbach, 1989), with other factors also playing a role (Ding et al., 2005). Orbitally-tuned records of the underlying red-clay sequence show a major weakening of the summer monsoon at 2.72 Ma (Sun et al., 2006; Figure 2) which coincides with the cold MIS G6. Between about 2.8 and 2.4 Ma, there also occurred the progressive aridification of Northwest Africa (Leroy and Dupont, 1994).

In central Europe, vegetation was changing from subtropical to boreal at around the same time (MIS G6–G4) (Willis et al., 1999). In Northwest Europe, an initial cooling likely representing MIS G6–G4 is reflected by the Reuverian B2 pollen substage, and this was followed by a severely cold climatic phase (Praetiglian pollen stage) directly correlated to MIS 100, 98 and 96 (2.54–2.43 Ma; Kuhlmann et al., 2006).

In Northern Eurasia, a major herbivore turnover between 2.6 and 2.2 Ma represents the emergence of the Palearctic zoogeographical province. It is characterized by the appearance of large modern ruminants and was driven by aridity as well as overall cooling and seasonal contrasts in temperature (Brugal and Croitor, 2007) that led to an opening of the landscape. The evolution of hominins and notably the emergence of the genus *Homo* between c. 2.6 and 2.45 Ma (Deino et al., 2006; Prat, 2007) were probably driven by the extreme climatic fluctuations at this time (Deino et al., 2006).

Base of the Quaternary

While the Quaternary is generally characterised by widespread Northern Hemisphere mid-latitude glaciation, cooling was both global and episodic. Multiple major cooling phases occurred between 2.8 and 2.4 Ma (MIS G10 to MIS 96), and their expression varied according to region (North Atlantic IRD at 2.74 Ma, loess–palaeosol accumulation in China at 2.6 Ma, severe cooling in NW Europe at 2.54 Ma, incoming sub-Antarctic molluscs to Wanganui Basin in New Zealand at 2.4 Ma [Pillans and Naish, 2004]). No single global event emerges as a fulcrum of change. Given that boundaries must be recognized unambiguously and widely, we note that the Gauss–Matuyama polarity boundary at 2.581 Ma (or 2.610 Ma, with a transition of 1.5 kyr, according to Deino et al., 2006), falls near the mid-point of this interval of global cooling. The base of the Gelasian Stage, defined by a GSSP at Monte San Nicola in Sicily, has an astrochronological age of 2.588 Ma. It occurs immediately above sapropel MPRS 250, corresponds to MIS 103 and is located about 1 m (20 kyrs) above the Gauss–Matuyama boundary (Rio et al., 1998). Given the close proximity of this existing GSSP to the Gauss–Matuyama boundary, and its calibration to the astrochronological time scale, the base-Gelasian GSSP is evidently well characterised also to define the base of the Quaternary.

Recommendation

In our scheme, the Quaternary Period/System, Pleistocene Epoch/Series, and Gelasian Age/Stage share the same GSSP at the base-Gelasian, which is dated at 2.588 Ma. In accepting the Holocene as an epoch distinct from the Pleistocene, we recognize the fundamental impact made by modern humans on an otherwise unremarkable interglacial; and we recall the remarks of Harland et al. (1990, p. 68) that including the Holocene as a Pleistocene stage 'would run counter to history and to an immense literature and would serve no great purpose', Consequently the terms Pleistocene and Quaternary are both needed. However, on hierarchical considerations, we support ICS's and INQUA's recommendation to lower the Plio–Pleistocene boundary, but accept that the Vrica GSSP continues to define the base of the Calabrian Stage. We accept the Gelasian Stage as a useful and already familiar term, and by extension generally support use of the provisional stages Calabrian, Ionian, and Tarantian (Cita et al., 2006; Cita, this issue). Our proposed scheme (Figure 1) meets INQUA requirements, obeys the principles of a hierarchical time scale, and respects historical precedents and established usage for the term Quaternary.

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References

Aguirre, E., and Pasini, G., 1985. The Pliocene–Pleistocene boundary: Episodes, 8, pp. 116–120.

Aiello, G., Barra, D., and Bonaduce, G., 1996. The genus *Cytheropteron* Sars, 1866 (Crustacea: Ostracoda) in the Pliocene–Early Pleistocene of the Mount San Nicola section (Gela, Sicily): Micropaleontology, 42, pp. 167–178.

Arduino, G., 1760. Sopra varie sue Osservazioni fatte in diverse parti del Territorio di Vicenza, ed altrove, appartenenti alla Teoria Terrestre, ed alla Mineralogia. Letter to Prof. Antonio Vallisnieri, dated 30th March, 1759. Nuova Raccolta di Opuscoli Scientifici e Filologici (Venice), v. 6 (1760).

Aubry, M.-P., Berggren, W.A., Van Couvering, J., McGowran, B., Pillans, B., and Hilgen, F., 2005. Quaternary: status, rank, definition, survival: Episodes, 28, pp. 118–120.

Balco, G., Rovey II, C.W., and Stone, J.O.H., 2005. The first glacial maximum in North America: Science, 307, p. 222.

Bartoli, G., Sarnthein, M., Weinelt, M., Erlenkeuser, H., Garbe-Schönberg, D., and Lea, D.W. 2005. Final closure of Panama and the onset of northern hemisphere glaciation: Earth and Planetary Science Letters, 237, pp. 33–44.

Berggren, W.A., 1998. The Cenozoic Era: Lyellian (chrono)stratigraphy and nomenclatural reform at the millennium. In: Blundell, D.J., and Scott, A.C. (eds), Lyell: the past is the key to the present: Geological Society, London, Special Publication, 143, pp. 111–132.

Berger, A., and Loutre, M.F., 1991. Insolation values for the climate of the last 10 million years: Quaternary Science Reviews, 10, pp. 297–317.

Bowen, D.Q., and Gibbard, P.L., 2007. The Quaternary is here to stay: Journal of Quaternary Science, 22, pp. 3–8.

Brugal, J.-P., and Croitor, R., 2007. Evolution, ecology and biochronology of herbivore associations in Europe during the last 3 million years: Quaternaire, 18, pp. 129–151.

Cita, M.B., Capraro, L., Ciaranfi, N., Di Stefano, E., Marino, M., Rio, D., Sprovieri, R., and Vai, G.B., 2006. Calabrian and Ionian: A proposal for the definition of Mediterranean stages for the Lower and Middle Pleistocene: Episodes, 29, pp. 107–114.

Cowie, J.W., and Bassett, M.G. (compilers) 1989. 1989 global stratigraphic chart with geochronometric and magnetostratigraphic calibration: Episodes, 12 (2), supplement, 1 sheet.

Deino, A.L., Kingston, J.D., Glen, J.M., Edgar, R.K., and Hill, A., 2006. Precessional forcing of lacustrine sedimentation in the late Cenozoic Chemeron Basin, Central Kenya Rift, and calibration of the Gauss/Matuyama boundary: Earth and Planetary Science Letters, 247, pp. 41–60.

Ding, Z.L., Derbyshire, E., Yang, S.L., Sun, J.M., and Liu, T.S., 2005. Stepwise expansion of desert environment across northern China in the past 3.5 Ma and implications for monsoon evolution: Earth and Planetary Science Letters, 237, pp. 45–55.

Driscoll, N.W., and Haug, G.H., 1998. A short circuit in thermohaline circulation: a cause for Northern Hemisphere Glaciation?: Science, 282, pp. 436–438.

Geirsdottir, A., and Eiriksson, J., 1994. Growth of an intermittent ice sheet in Iceland during the late Pliocene and early Pleistocene: Quaternary Research, 42, pp. 115–130.

Gradstein, F.M., Ogg, J.G., Smith, A.G., Bleeker, W., and Lourens, L.J., 2004. A new geologic time scale with special reference to the Precambrian and Neogene: Episodes, 27, pp. 83–100, with accompanying chart.

Gradstein, F.M., Ogg, J.G., and Smith, A.G. (eds.), 2005. A Geologic Time Scale 2004: Cambridge University Press, Cambridge, i–xix, pp. 1–589 [Imprinted 2004].

Gibbard, P.L. et al. (12 co-authors), 2005. What status for the Quaternary?: Boreas, 34, pp.1–6.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., and Smith, D.G., 1990. A geologic time scale: Cambridge University Press, Cambridge, i–xvi, pp. 1–263.

Haug, G.H., Ganopolski, A., Sigman, D.M., Rosell-Mele, A., Swann, G.E.A., Tiedemann, R., Jaccard, S.L., Bollmann, J., Maslin, M.A., Leng, M.J., and Eglinton, G., 2005. North Pacific seasonality and the glaciation of North America 2.7 million years ago: Nature, 433, pp. 821–825.

Head, M.J., 2007. Tracking the status and duration of the Quaternary – a resolution in sight? CANQUA Annual Meeting: Carleton University, Ottawa, June, 2007.

Kameo, K., and Sato, T., 2000. Biogeography of Neogene calcareous nannofossils in the Caribbean and eastern equatorial Pacific – floral response to the emergence of the Isthmus of Panama: Marine Micropaleontology, 39, pp. 201–218.

Kleiven, H.F., Jansen, E., Fronval, T., and Smith, T.M., 2002. Intensification of Northern Hemisphere glaciations in the circum Atlantic region (3.5–2.4 Ma)—ice-rafted detritus evidence: Palaeogeography, Palaeoclimatology, Palaeoecology, 184, pp. 213–223.

Kuhlmann, G., Langereis, C.G., Munsterman, D., van Leeuwen, R.-J., Verreussel, R., Meulenkamp, J.E., and Wong, Th.E., 2006. Integrated chronostratigraphy of the Pliocene–Pleistocene interval and its relation to the regional stratigraphical stages in the southern North Sea region. Netherlands: Journal of Geosciences–Geologie en Mijnbouw, 85, pp. 19–35.

Leroy, S., and Dupont, L., 1994. Development of vegetation and continental aridity in northwestern Africa during the Late Pliocene: the pollen record of ODP Site 658: Palaeogeography, Palaeoclimatology, Palaeoecology, 109, pp. 295–316.

Lisiecki, L.E., and Raymo, M.E., 2005. A Pliocene–Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records: Paleoceanography, v. 20, PA1003, doi:10.1029/2004PA001071.

Lisiecki, L.E., and Raymo, M.E., 2007. Plio-Pleistocene climate evolution: trends and transitions in glacial cycle dynamics: Quaternary Science Reviews, 26, pp. 56–69.

Lourens, L., Hilgen, F., Shackleton, N.J., Laskar, J., and Wilson, D., 2005. The Neogene Period. In: Gradstein, F.M., Ogg, J.G., and Smith, A.G (eds.), A Geologic Time Scale 2004: Cambridge University Press, Cambridge, pp. 409–440 [Imprinted 2004].

Monegatti, P., and Raffi, S., 2001. Taxonomic diversity and stratigraphic distribution of Mediterranean Pliocene bivalves: Palaeogeography, Palaeoclimatology, Palaeoecology, 165, pp. 171–193.

Mudelsee, M., and Raymo, M.E., 2005. Slow dynamics of the Northern Hemisphere glaciation. Paleoceanography, 20: PA4022, doi:10.1029/2005PA001153.

Pillans, B., 2007. Defining the Quaternary: Where do we go from here?: Stratigraphy, 4, pp. 145–149.

Pillans, B., and Naish, T., 2004. Defining the Quaternary: Quaternary Science Reviews, 23, pp. 2271–2282.

Prat, S., 2007. The Quaternary boundary: 1.8 or 2.6 millions years old? Contributions of early *Homo*: Quaternaire 18, pp. 99–107.

Remane, J. (compiler), 2000. International Stratigraphic Chart: International Union of Geological Sciences, and UNESCO Division of Earth Sciences, Paris.

Remane, J., and Michelsen, O., 1998. Report on the vote about the demand to lower the Plio–Pleistocene boundary (PPB). Unpublished report of the International Commission on Stratigraphy, dated 21 December 1998, 3 pp. [reproduced in Newsletter no. 6 of the International Subcommission on Stratigraphic Clasification, December 2004, pp. 5–7.]

Roveri, M., and Taviani, M., 2003. Calcarenite and sapropel deposition in the Mediterranean Pliocene: shallow- and deep-water record of astronomically driven climatic events: Terra Nova, 15, pp. 279–286.

Ruddiman, W.F., and Kutzbach, J.E., 1989. Forcing of late Cenozoic northern hemisphere climate by plateau uplift in southern Asia and the American West: Journal of Geophysical Research, 94, pp. 18409–18427.

Rio, D., Sprovieri, R., Castradori, D., and Di Stefano, E., 1998. The Gelasian Stage (Upper Pliocene): A new unit of the global standard chronostratigraphic scale: Episodes, 21, pp. 82–87.
Salvador, A., 2006a. The Tertiary and the Quaternary are here to stay: AAPG Bulletin, 90, pp. 21–30.
Salvador, A., 2006b. A stable Cenozoic geologic time scale is indispensable: Episodes, 29, pp. 43–45.
Sigman, D.M., Jaccard, S.L., and Haug, G.H., 2004. Polar ocean stratification in a cold climate: Nature, 428, pp. 59–63.
Suc, J.-P., Bertini, A., Leroy, S.A.G., and Suballyova, D., 1997. Towards the lowering of the Pliocene/Pleistocene boundary to the Gauss–Matuyama reversal: Quaternary International, 40, pp. 37–42.
Sun, Y.B., Clemens, S.C., An, Z.H., and Yu, Z.W., 2006. Astronomical timescale and palaeoclimatic implication of stacked 3.6-Myr monsoon records from the Chinese Loess Plateau: Quaternary Science Reviews, 25, pp. 33–48.
St. John, K.E.K., 2004. Evidence that's an ocean apart: co-varying records of ice-rafted debris flux and Plio–Pleistocene bipolar ice sheet disintegration: The Sedimentary Record, 2, pp. 4–8.
Vaccari, E., 2006. The "classification" of mountains in eighteenth century Italy and the lithostratigraphic theory of Giovanni Arduino (1714–1795): Geological Society of America Special Paper, 411, pp. 157–177.
Versteegh, G.J.M., 1997. The onset of major Northern Hemisphere glaciations and their impact on dinoflagellate cysts and acritarchs from the Singa section, Calabria (southern Italy) and DSDP Holes 607/607A (North Atlantic): Marine Micropaleontology, 30, pp. 319–343.
Walsh, S.L., 2006. Hierarchical subdivision of the Cenozoic Era: A venerable solution, and a critique of current proposals: Earth-Science Reviews, 78, pp. 207–237.
Walsh, S.L., in press. The Neogene: origin, adoption, evolution, and controversy: Earth-Science Reviews.
Willis, K.J., Kleczkowski, A., and Crowhurst, S.J., 1999. 124,000-year periodicity in terrestrial vegetation change during the late Pliocene epoch: Nature, 397, pp. 685–688.

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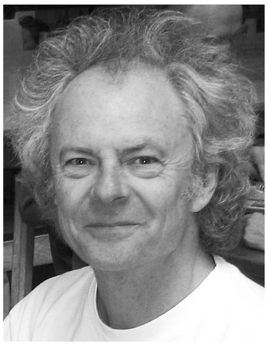

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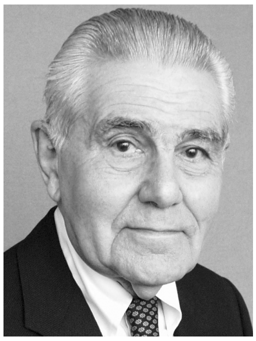
In Memorium Amos Salvador 1923–2007



Amos Salvador was Professor Emeritus in the Department of Geological Sciences at The University of Texas at Austin. He was well known for his contributions to stratigraphic classification, research on the Gulf of Mexico and writings on the future of energy resources. As Chair of the International Commission on Stratigraphy's Subcommission on Stratigraphic Classification, he was the Editor of the second edition of the International Stratigraphic Guide (1994) and co-editor of an abridged version. Through these publications Salvador contributed to international agreement on principles of stratigraphic classification, making possible greater communication, coordination and understanding of some of geology's fundamental systems of classification. Previously, he worked for the Mene Grande Oil Company, a Venezuelan subsidiary of Gulf Oil, where he was advised by Hollis Hedberg, who later taught at Princeton University. Salvador was awarded a Ph.D., which he completed in 1950, at Stanford University. From 1950 to 1955, he was employed by Gulf Oil as a regional and surface geologist covering North Africa, Europe and South America. He left Gulf Oil in 1955 to join an affiliate of Esso (now ExxonMobil) in Venezuela and then until 1980 for several Esso affiliates. He retired as chief geologist of the Exxon Company, U.S.A. in 1980 to take up a position in the Department of Geological Sciences in The University of Texas at Austin, where he was first the Alexander Deussen Professor of Energy Resources and, after 1990, the Morgan J. Davis Professor of Petroleum Geology. The Department of Geological Sciences recognised Salvador's dedicated teaching by awarding him the Houston Oil & Minerals Corporation Faculty Excellence Award in 1988.

In recent years, Salvador made it a mission to protest against efforts by the International Commission on Stratigraphy to eliminate the Tertiary and Quaternary periods from official classifications of the geological time scale. Although the Tertiary and Quaternary are widely accepted and used as periods within the Cenozoic Era, both terms were omitted from the Geologic Time Scale published in 2004. Salvador contended this was folly and that 'the Tertiary and the Quaternary are here to stay', as long as geologists continue to use the terms.

He died, aged 84, on 2nd December 2007 of complications from pneumonia and a malignant brain tumour. He is survived by his wife Lynn, and his children Phillip, Michael and Rosario.

This volume of papers is dedicated to his memory. We are indebted to Mark Cloos (Department of Geological Sciences, The University of Texas at Austin) for allowing us to reproduce excerpts from his obituary of Amos Salvador.

Philip Gibbard & Martin J. Head

by Lucas J. Lourens

On the Neogene–Quaternary debate

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A proposed resolution to the current Neogene–Quaternary debate involves independent, non-overlapping status for the two units and harks back to Lyell's original denotation of the terms Older and Newer Pliocene.

The Astronomical Tuned Neogene Time Scale 2004

The standard methods to construct geological time scales changed drastically with the advent of the astronomical dating method, which relies on tuning sedimentary cycles or cyclic variations in climate proxy records to target curves derived from astronomical solutions for the solar, planetary and Earth-Moon systems. A major breakthrough of the astronomical theory was established by Milutin Milanković between 1915 and 1940 when he worked out a solid mathematical basis of the late Pleistocene climate cycles (Milankovitch, 1941). With the success of ocean drilling and the development of stable oxygen isotopes ($\delta^{18}O$) as proxy for global climate change, the astronomical time scale was extended step by step further back in time. Concomitantly, integrated stratigraphic studies of late Cenozoic land-based marine sequences in the Mediterranean yielded an independent astrochronology with many calcareous plankton events, magnetic reversals and Global Stratotype Section and Points (GSSP's), apart from the Aquitanian, directly tied to it. Milestones were the accomplishment of tuning the Brunhes Chron (Johnson, 1982), the Pleistocene (Shackleton et al., 1990), the Late Pliocene (Shackleton et al., 1990; Hilgen, 1991a), the Early Pliocene (Hilgen, 1991b; Tiedemann et al., 1994) and Miocene (Shackleton et al., 2000). Lourens et al. (1996a) verified and slightly modified the astronomical time scale for the Pliocene and early Pleistocene resulting from a comparison with different astronomical solutions. In 2004, the first complete Astronomical Tuned Neogene Time Scale (ATNTS2004) was incorporated in the standard geological time scale (Lourens et al., 2004).

Astronomically tuned ages are typically presented to three decimals without error bar, being the age (in kyrs) of the corresponding peak in the selected target curve calculated from a particular astronomical solution. The main uncertainties in astronomical dating and, hence, the astronomical ages in particular, depend on the accuracy of the astronomical solution and the correctness of the tuning. The exact error in the presently used La2004 (Laskar et al., 2004) solution is difficult to calculate due to the complexity of the solution, but the largest uncertainty (i.e., less than a few kyr for the past 3 million years) is thought to be related to the dissipative evolution of the Earth-Moon system; i.e., the dynamical ellipticity of the Earth and/or the tidal dissipation by the Moon (Laskar, 1999; Lourens et al., 2001; 2004).

Another potential error in the astronomical ages stems from the uncertainty in the phase relation between the astronomically-forced variations in the climate proxy records used for tuning and the initial insolation forcing. A fundamental assumption used in many $\delta^{18}O$ chronologies is that they are tuned to an ice sheet model in which the phase lags of the isotopic signal at the main astronomical frequencies (obliquity and precession) are those of a single-exponential system, including a fixed ice sheet response time and a non-linearity coefficient (Imbrie and Imbrie, 1980). In their recent global stacked benthic oxygen isotope chronology (LR04) Lisiecki and Raymo (2005 and references therein) applied different values for both parameters to correct for the transition from the nearly ice-free Northern Hemisphere during the early Pliocene (5.3–3.0 Ma) to the full glacial conditions of the late Pleistocene. Although this tuning procedure takes the long-term trends in global ice volume into account, it still fails to resolve the geometry and response time of individual glacial cycles. Moreover, the uncertainty in the size-prediction of ice sheets, and hence their response times, is augmented by the fact that benthic foraminiferal $\delta^{18}O$ records preserve not only an ice-volume, but also a deep-water temperature component (Shackleton et al., 1990; Bintanja et al., 2005). Nevertheless, the uncertainty in the absolute timing of the glacial–interglacial cycles is supposed to be less than ~5 kyr. Similarly, the uncertainty in the astrochronology of the Mediterranean is on the order of 3 kyrs for each calibration point, depending upon the assumed phase relation between insolation and the cyclic sedimentary (i.e., sapropels) expression (Lourens et al., 2004).

Global climate change over the past 5.3 Ma

Figure 1 displays the variations in the global benthic $\delta^{18}O$ record (Lisiecki and Raymo, 2005) spanning the current Pliocene, Pleistocene and Holocene Epochs. This record depicts a major change towards heavier values around 4 Ma, interpreted as reflecting the beginning of a cooling trend associated with the growth of major Northern Hemisphere ice caps superimposed on short-term obliquity-dominated glacial cycles (Shackleton, 1997). At 3.3 Ma a marked cooling event occurs during the Mammoth subchron (Prell, 1984; Keigwin, 1986). Approximately at this point the background values of the LR04-stacked $\delta^{18}O$ record passed present-day values for the first time.

Marine Isotopic Stage (MIS) 100 to 96 are clearly-defined glacial periods and are associated with a significant amount of ice rafted debris (IRD) in the North Atlantic (Shackleton et al., 1984; Raymo et al., 1989). The immediately preceeding MIS102-114 are less amplified, but already contain trace amounts of IRD in the Northern Atlantic Deep Sea Drilling (DSDP) Sites 607 and 609 (Raymo et al., 1989). Besides isotopic evidence, this climatic deterioration is denoted by the first occurrence of the extinct polar water planktonic foraminiferal species *Neogloboquadrina atlantica* in the Mediterranean during MIS 110 at 2.72 Ma (Lourens et al., 1996a). *Neogloboquadrina atlantica* became extinct at the end of MIS 96 (Zachariasse et al., 1990), indicating a return to warmer background climate conditions between the less prominent glacial cycles of MIS 96 to 82. Two punctuated glacial stages, MIS 78 and 82, occur again around 2.1 Ma.

The Pliocene/Pleistocene boundary at 1.806 Ma (Hilgen, 1991a; Lourens et al., 1996b; 1998; 2004) as defined in the Vrica section (Aguirre and Pasini, 1985) is not represented by an extreme climatic event in the global $\delta^{18}O$ record (Figure 1), but its significance in terms of cooling is corroborated by the first common occurrence of sinistrally-coiled *Neogloboquadrina pachyderma* in the North Atlantic DSDP Site 607 and the Mediterranean (Lourens and Hilgen, 1997). Until MIS 25, the early Pleistocene is characterized

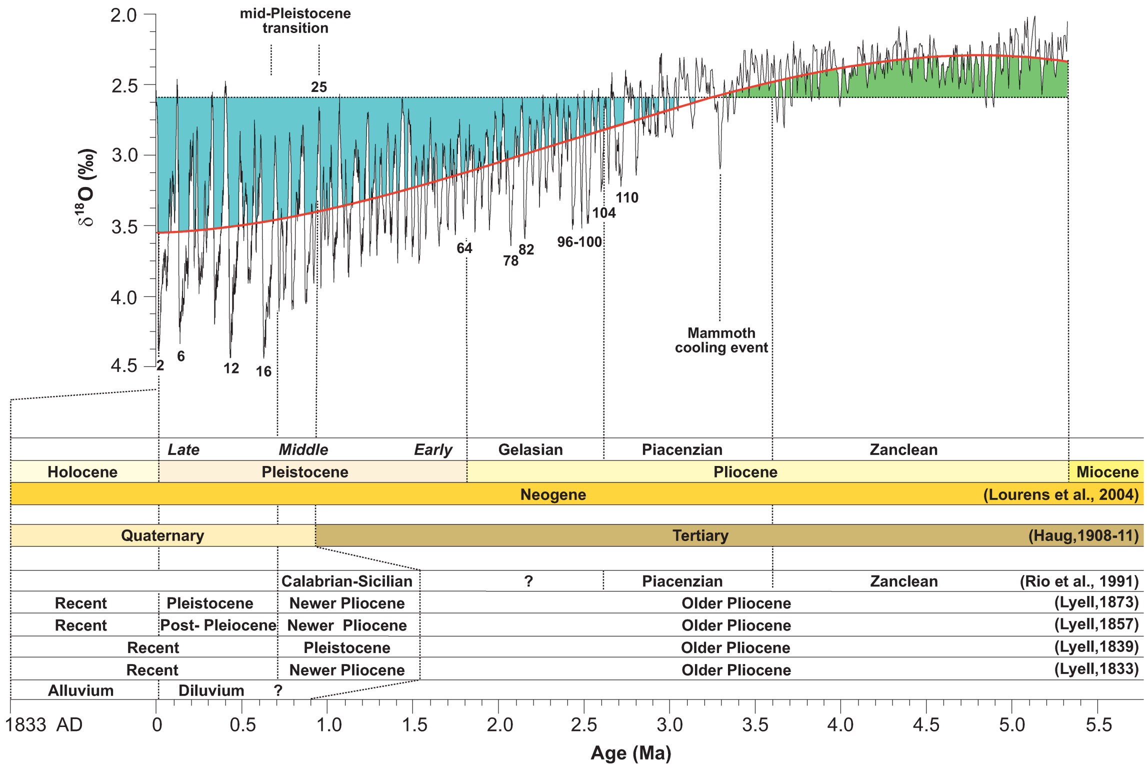

***Figure 1** Comparison between major events in the global benthic foraminiferal δ18O stacked record (Lisiecki and Raymo, 2005) and the historical (Lyell, 1833–73; Haug, 1908–1911; Rio et al., 1991) and present (Lourens et al., 2004) chronostratigraphic subdivision of the late Cenozoic.*

by very regular glacial cycles. Thereafter, a marked transition (known as the mid-Pleistocene transition) to the approximately 100 kyr dominated and strongly amplified glacial-interglacial oscillations occurred. Four major glacial periods stand out in the late Pleistocene $\delta^{18}O$ record; MIS 2, 6, 12 and 16. Only during these glacials were climate conditions in Europe cold enough to permit the Fennoscandian ice cap to expand south of the Baltic (Boulton et al., 1997). Moreover, these intervals correspond with the thickest units (i.e., cycles B, C, F and H) in the loess–palaeosol record of Central Europe (Kukla, 1975).

The Plio–Pleistocene and Neogene–Quaternary debate

In 2007 the International Commission on Stratigraphy (ICS) held a ballot to place the Quaternary System above the Neogene with its base at the GSSP of the Gelasian Stage. Following the ballot, which was passed with a majority of votes, an official proposal was sent to the International Union of Geological Sciences (IUGS). The main arguments in favor of this proposal are that the Quaternary is of special significance in terms of climate cycles and human evolution, and that the historical usage of the term Neogene has been variable. In turn, arguments in favor of retaining the Neogene extending to the Recent are its original definition, its widely adopted concept in terms of (marine) biostratigraphical zonation schemes, and also that its astrochronology has now become an integral part of the late Cenozoic chronostratigraphic time scale. Moreover, in view of the fact that the Primary, Secondary and Tertiary have been eliminated from the geologic time scale, it is legitimate to ask as to why the Quaternary should still remain a part of the standard geologic time scale? In fact, the climatic argument to define the Quaternary as the glacial age (c.f. Forbes 1846) is now no longer strictly correct, since extensive ice-rafted debris, including macroscopic dropstones, have been identified in upper Eocene to lower Oligocene and in upper middle to upper Miocene sediments in the Norwegian-Greenland Sea, indicating glaciations of East Greenland long before 2.6 Ma (Wolf-Welling et al., 1996; Thiede et al., 1998; Eldrett et al., 2007).

The recent historical overview of Stephen L. Walsh (2008) on the origin, adoption, evolution, and controversy of the term Neogene (Hörnes, 1853, 1864) proves on the other hand that historical arguments to extend the Neogene to and including the Recent (Lyell, 1857) and Holocene of Gervais (1867; see Berggren, 1998) are difficult to substantiate from the original publications and communications of Hörnes. But, it also makes clear that whether or not the Diluvium (or post-Pleiocene sensu Lyell, 1857) was part of the Neogene, the latter term certainly included various Newer Pliocene (Lyell, 1857) deposits that are now considered to be Early, Middle and possibly even Late Pleistocene in age (Rio et al., 1991; Vai, 1997; Walsh, 2008) (Figure 1).

The current Neogene–Quaternary debate as such does not originate from the proposition to lower the base of the Quaternary (and hence the top of the Tertiary; Head et al., this volume), but from the fact that this proposal decapitates the Neogene as well as extending the Pleistocene Series to include strata that for more than a century and a half have been considered by (marine) stratigraphers to be Pliocene deposits (Figure 1). Several (compromise) proposals that have been submitted to unify the opposing viewpoints (see Ogg, 2004; Pillans and Naish, 2004; Aubry et al., 2005; Walsh, 2006) have not garnered broad support from the (late Cenozoic) chronostratigraphic community, largely because they lack a chronostratigraphic hierarchy.

Another major shortcoming in the present debate is that the arguments of lowering the Pleistocene/Pliocene (and Tertiary/Quaternary) boundary to 2.6 Ma (i.e., Head et al., and Ogg and Pillans this volume) are on historical grounds no more logical than raising it to ~0.6 Ma. Moreover, it could be argued that the climatic transition between 0.6 and 0.9 Ma from the less-amplified 41 kyr glacial cycles to the large scale 100 kyr dominated glacial cycle had a larger impact on ecosystems, including human evolution (origin of *Homo sapi-*

ens), than the gradual transition around 2.7 Ma (Figure 1). Finally, in terms of climate science, only the last ~0.6 Myr of Earth's history can be studied in all geological archives, including ice core records, making the younger option, also in that sense, more relevant than the older option.

To conclude, I am of the opinion that a general consensus on the *"time war over the Period we live in debate"* (Kerr, 2008) can only be reached if the Neogene remains extended to the present, and that the position of the present Pliocene/Pleistocene boundary remains unchanged. If the Quaternary (and Tertiary) retains a formal chronostratigraphic status in the standard Geological Time Scale with its base at a refined Gelasian GSSP (i.e., the FO *N. atlantica* in the Mediterranean at 2.72 Ma) then a solution for the hierarchical inconsistency of the chronostratigraphic chart may have been found. Such a solution would hark back to Lyell's original Older and Newer Pliocene Epochs, could upgrade the present Upper, Middle and Lower Pliocene Subseries to separate Late Pliocene and Early Pliocene Epochs with its boundary at 2.72 Ma. In addition, the present Pleistocene could be split into separate Early, (Middle) and Late Pleistocene Epochs.

With the renewed introduction of the Early and Late Pliocene as separate Epochs, all stratigraphic criteria to define the base of the Quaternary as a Subperiod (Subsystem) of the Neogene are fulfilled. Namely 1) the boundary-stratotype is fixed by its lower boundary, 2) it follows the principles of "base defines boundary", 3) the boundary stratotype can be fixed in marine sediments, 4) it respects the historical usage (albeit not a true historical priority and age), and 5) it focuses as much as possible on the best correlation potential, which is in this case the base of the (refined) Gelasian Stage (Rio et al., 1998) as the basal unit or the base of the Late Pliocene Epoch. Hence the Quaternary will encompass the Late Pliocene, Early, (Middle) and Late Pleistocene and Holocene Epochs, thereby respecting its historical usage in its broadest sense and its consistence with the principles of hierarchical classification.

A redefinition of the Quaternary as Subperiod will imply that an official end has come to the Tertiary (Arduino, 1760) as a formal unit of the GTS (see also Pillans, 2004). But, if the Tertiary and Quaternary are to be formally defined and ranked again (Walsh, 2006; Head et al., this volume) then one should rank them as Suberas of the Cenozoic (Aubry et al., 2005) and split the Neogene into an Early, Middle and Late Neogene Period. A split Neogene is not new: Renevier (1874; 1897) for instance already included the Holocene, Plistocene (Renevier's spelling) and Pliocene in his Recent Neogenic, and Prepliocene and Miocene within the Ancient Neogenic, whereas the Nummulitic represented the Paleogene. Accordingly, the Middle–Late Neogene boundary would correspond to the base of the (refined) Gelasian Stage or Early–Late Pliocene boundary, and the Late Neogene would encompass the same time interval as the Quaternary, thereby respecting the usage of both terms in the current literature.

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References

Aguirre, E., and Pasini, G., 1985. The Pliocene–Pleistocene Boundary: Episodes, v. 8, pp. 116–120.

Arduino, 1760. Nuovo raccolta di opuscoli scientifici e filologici del padre abate Anigiolo Calogiera, v.6, pp.99–180.

Aubry, M.-P., Berggren, W.A., Van Couvering, J.A., McGowran, B., Pillans, B., and Hilgen, F.J., 2005. Quaternary: status, rank, definition, and survival: Episodes, v.28, pp.118–120.

Berggren,W.A., 1998. The Cenozoic Era: Lyellian (chrono)stratigraphy and nomenclatural reform at the millenium. *In*: Blundell, D.J., Scott, A.C. (Eds.), Lyell: the Past is the Key to the Present: Geological Society, Special Publication, vol. 143. Geological Society, London, pp. 111–132.

Bintanja, R., Wal, R.S.W. van de, and Oerlemans, J., 2005. Modelled atmospheric temperatures and global sea levels over the past million years: Nature, v.437, pp. 125–128.

Boulton, G. S., Dalgleish, N., Hulton, N. and Van Gijssel, K., 1997. Reconstruction of mid- and late Quaternary climate and environmental change in Europe. *In* Simulation of the effects of long-term climatic change on groundwater flow and the safety of geological disposal sites, Report EUR 17793 EN (Ed. by G. S. Boulton and F. Curle), pp. 29–66. Office for Official Publications of the European Community, Luxembourg.

Eldrett, J.S., I.C. Harding, P.A. Wilson, E. Butler and A.P. Roberts., 2007. Continental ice in Greenland during the Eocene and Oligocene: Nature, v. 446, pp.176–179.

Forbes, E., 1846. On the connection between the distribution of the existing fauna and flora of the British Isles, and the geological changes which have affected their area, especially during the epoch of the Northern Drift: Great Britain Geological Survey Memoir, v.1, pp.336–342.

Gervais, P., 1867–9. Zoologie et paleontology générales. Nouvelles recherches sur les animaux vertétebrés et fossiles, Paris, 263 pp.

Haug, E., 1908–1911. Les Périodes géologiques: Traité de Géologie, 11, pp. 1766–1776.

Head, M.J., P.L. Gibbard, and A. Salvador. The Tertiary and Quaternary: status, duration and future: Episodes (submitted).

Hilgen, F. J., 1991a. Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the Geomagnetic Polarity Time Scale: Earth and Planetary Science Letters, v. 104, pp.226–244.

Hilgen, F.J., 1991b. Extension of the astronomically calibrated (polarity) time scale to the Miocene–Pliocene boundary: Earth Planet. Sci. Lett., v.107, pp.349–368.

Hörnes, M., 1853. Mitteilung an Prof. Bronn gerichtet: Wien, 3. Okt., 1853. Neues Jahrb. Mineral: Geol. Geogn. Petrefaktenkd., pp. 806–810.

Hörnes, M., 1864. V. Die fossilen Mollusken des Tertiärbeckens von Wien. Jahrb: Geol. Reichsant., v.14, pp.509–514.

Imbrie, J, and Imbrie, J.Z., 1980. Modelling the climatic response to orbital variations: Science, v. 207, pp. 943–953.

Johnson, R. G., 1982. Brunhes–Matuyama magnetic reversal dated at 790,000 yr BP by marine–astronomical correlations: Quaternary Research, v.17, pp.135–147.

Keigwin, L.D., 1986. Pliocene stable-isotope record of Deep Sea Drilling Project Site 606: Sequential events of $\delta^{18}O$ enrichment beginning at 3.1 Ma. *In* Ruddiman, W. E, Kidd, R. B., Thomas, E., et al., Init. Repts. DSDP, 94: Washington (U.S. Govt. Printing Office), pp.911–920.

Kerr, R.A., 2008. A time war over the Period we live in:Science, v.318, pp.402–403.

Kukla, G. J., 1975. Loess stratigraphy of Central Europe. *In* After the Australopithecines: stratigraphy, ecology, and culture change in the Middle Pleistocene (Ed. by K. W. Butzer and G. L. Isaac), pp. 99–188. Mouton, The Hague/Paris.

Laskar, J., 1999. The limits of Earth orbital calculations for geological time scale use: Phil. Trans. R. Soc. Lond. A., 357, pp.1735–1759.

Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A., and Levrard, B., 2004. A long term numerical solution for the insolation quantities of the Earth: Astron. Astrophys., v. 428, pp. 261–285.

Lisiecki, L.E., and Raymo, M.E., 2005. A Pliocene–Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records: Paleoceanography 20, PA1003.

Lourens, L.J., and Hilgen, F.J., 1997. Long–periodic variatons in the Earth's obliquity and their relation to third-order eustatic cycles and late Neogene glaciations, Quat. Int., 40, pp. 43–52.

Lourens, L.J., Hilgen, F.J., Zachariasse, W.J., van Hoof, A.A.M., Antonarakou, A. and Vergnaud-Grazzini, C., 1996a. Evaluation of the Plio–Pleistocene astronomical time scale: Paleoceanography, v. 11, pp. 391–413.

Lourens, L.J., Hilgen, F.J., Raffi, I., and Vergnaud-Grazzini, C., 1996b. Early Pleistocene chronology of the Vrica section (Calabria, Italia): Paleoceanography, v. 11, pp. 797–812.

Lourens, L.J., Hilgen, F.J., and Raffi, I., 1998. Base of large Gephyrocapsa and astronomical calibration of early Pleistocene sapropels in ODP sites 967 and 969: Solving the chronology of the Vrica section. ODP Sci. Results, v.160, pp.191–197.

Lourens, L.J., Wehausen, R., and Brumsack, H.J., 2001. Geological constraints on tidal dissipation and dynamical ellipticity of the Earth over the past three million years: Nature v.409, pp.1029–1033.

Lourens, L., Hilgen, F., Shackleton, N.J., Laskar, J., Wilson, D., 2004. The Neogene Period. *In:* Gradstein, F.M., Ogg, J.G., Smith, A. (Eds.), A Geologic Time Scale 2004: Cambridge University Press, Cambridge, UK, pp. 409–440.

Lyell, C., 1833. Principles of Geology : being an inquiry how far the former changes of the earth's surface are referable to causes now in operation. Volume III. London: John Murray, 398 pp.

Lyell, C., 1839. Nouveaux éléments de géologie. Pitois-Levranet., Paris, 648 pp.

Lyell, C., 1857. Supplement to the fifth edition: London, John Murray, 40 pp.

Lyell, C., 1873. The geological evidences of the antiquity of man: with an outline of glacial and post-tertiary geology and remarks on the origin of species; with special reference to man's first appearance on the earth: London, John Murray, 572 pp.

Milanković, M.M., 1941. Kanon der Erdbestrahlung und seine Anwendung auf das Eiszeitenproblem. Royal Serbian Academy, Section of Mathematical and Natural Sciences, Special Publication 32. Belgrade: Royal Serbian Academy, p. 633.

Ogg, J.G., 2004. Introduction to concepts and proposed standardization of the term "Quaternary": Episodes, v. 27, pp. 125–126.

Pillans, B., 2004. Proposal to redefine the Quaternary: Episodes, v. 27, pp. 127.

Pillans, B., and T., Naish, 2005. Defining the Quaternary: Quaternary Science Reviews, v. 23, pp. 2271–2282.

Prell, W. L., 1984. Covariance patterns of foraminiferal $\delta^{18}O$: An evaluation of Pliocene ice volume changes near 3.2 million years ago: Science, v. 226, pp. 692–694.

Raymo, M.E., Ruddiman, W. F., Backman, J., Clement B. M. & Martinson, D. G., 1989. Late Pliocene variation in northern Hemisphere ice sheets and North Atlantic deep water circulation: Paleoceanography, v. 4, pp. 413–446.

Renevier, E., 1874. Tableau des terrains sédimentaires formés pendant les époques de la phase organique du globe terrestre: Bulletin Societd Vaudoise Sciences Naturelles, 12(70), table 3; 13(72), pp.218–252.

Renevier, E., 1897. Chronographe géologique; seconde édition du Tableau des terraines sédimentaires. *In*: VI Congrés géologique international, Compte-Rendu: Georges Bridel, Lausanne, pp.522–595, 12 tables.

Rio, D., Sprovieri, R., and Thunell, R., 1991. Pliocene-lower Pleistocene chronostratigraphy: A re-evaluation of Mediterranean type sections: Geol. Soc. Am. Bull., 103, pp. 1049–1058.

Rio, D., Sprovieri, R., Castradori, D., and Di Stefano, E., 1998. The Gelasian Stage (Upper Pliocene): A new unit of the global standard chronostratigraphic scale: Episodes, 21, pp.82–87.

Shackleton, N.J., 1997. The deep-sea sediment record and the Pliocene–Pleistocene boundary: Quat. Int., v. 40, pp. 33–35.

Shackleton, N. J., Backman, J., Zimmerman, H., et al., 1984, Oxygen-isotope calibration of the onset of ice-rafting in DSDP site 552A: history of glaciation in the North Atlantic region: Nature, v. 307, pp. 620–33.

Shackleton, N.J., Berger, A., and Peltier, W.R., 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP site 677: Trans. Roy. Soc. Edin., v. 81, pp. 251–261.

Shackleton NJ, Hall MA, Raffi I, Tauxe L, Zachos J, 2000. Astronomical calibration age for the Oligocene–Miocene boundary: Geology, v. 28, pp.447–450.

Thiede, J., Winkler, A., Wolf-Welling, T., Eldholm, O., Myhre, A.M., Baumann, K.-H., Henrich, R., and Stein, R., 1998. Late Cenozoic history of the polar north Atlantic: Results from ocean drilling: Quaternary Science Rev., v. 17, pp. 185–208.

Tiedemann, R., Sarnthein, M., and Shackleton, N.J., 1994. Astronomical timescale for the Pliocene Atlantic $\delta^{18}O$ and dust flux records of ODP Site 659: Paleoceanography, v.9, pp. 619–638.

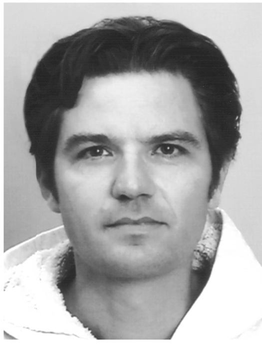
Vai, G.B., 1997, Twisting or stable Quaternary boundary? A perspective on the glacial Late Pliocene concepts: Quaternary International, v.40, 11–22.

Walsh, S.L., 2006. Hierarchical subdivision of the Cenozoic Era: A venerable solution, and a critique of current proposals: Earth Science Reviews, v.78, pp. 207–237.

Walsh, S.L., 2008. The Neogene: Origin, adoption, evolution and controversy: Earth Science Reviews (in press).

Wolf-Welling, T.C.W., M. Cremer, S. O'Connell, A. Winkler, and J. Thiede, 1996. Cenozoic Arctic Gateway paleoclimate variability: Indications from changes in coarse-fraction composition (ODP Leg 151). *In*: Thiede, J., Myhre, A.M., Firth, J., et al., Proceedings Ocean Drilling Program, Scientific Results, 151, pp.515–567.

Zachariasse, W.J., Gudjonsson, L., Hilgen, F.J., Lourens, L.J., Verhallen, P.J.J.M., Langereis, C.G., and Zijderveld, J.D.A., 1990. Late Gauss to early Matuyama invasions of Neogloboquadrina atlantica in the Mediterranean and associated record of climatic change: Paleoceanography, v.5, pp. 239–252



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Global chronostratigraphical correlation table for the last 2.7 million years

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The table provides a correlation of chronostratigraphical subdivisions of late Cenozoic geological time, spanning the last 2.7 million years. The formal division of the Quaternary is the responsibility of the International Commission on Stratigraphy's (ICS) Subcommission on Quaternary Stratigraphy (SQS), in partnership with the International Union for Quaternary Research's (INQUA) Commission on Stratigraphy and Chronology (SACCOM). This is the third published version of the chart. Earlier versions are Gibbard et al., 2004, 2005. See http://www.quaternary.stratigraphy.org.uk/correlation/ *for history.*

Chronostratigraphy and the base of the Quaternary

The timescale is based on the internationally-recognised formal chronostratigraphical/geochronological subdivisions of time: the Phanerozoic Eonathem/Eon; the Cenozoic Erathem/Era; the Quaternary System/Period; the Pleistocene and Holocene Series/Epoch, and finally the Early/Lower, Middle, Late/Upper Pleistocene Subseries/Subepoch. At present the Subseries (Subepoch) divisions of the Pleistocene are being formalised. Series, and thereby systems, are formally-defined based on Global Stratotype Section and Points (GSSP) of which two (Holocene and Pleistocene Series) have been ratified for the Quaternary System. The currently ratified base of the Pleistocene is defined in a GSSP at Vrica in Southern Italy, (Aguirre and Pasini, 1985), with an age of ~1.8 Ma. However, it is proposed to define the base of the Quaternary/Pleistocene at 2.58 million years from Monte San Nicola, also in southern Italy, which is the current GSSP for the Pliocene Gelasian Stage (Rio et al., 1994, 1998).

Since 1948 there has been a consensus that the boundary should be placed at the first evidence of climatic cooling of ice-age magnitude. This was the original basis for placing the boundary at ~1.8 Ma in marine sediments at Vrica in Calabria, in Italy (Aguirre & Pasini, 1985). It is now known that a major cooling occurred earlier, at c. 2.55 million years in the Mediterranean (Cita, this issue), and even earlier cooling events are known from the Pliocene. Since its definition at 1.8 Ma there has been strong pressure for the basal Quaternary/Pleistocene boundary to be moved downwards to better reflect the initiation of major global cooling (Pillans and Naish, 2004; Gibbard et al., 2005; Bowen & Gibbard, 2007), effectively corresponding to the Gauss/Matuyama magnetic Chron boundary (e.g., Partridge, 1997; Suc et al., 1997). See discussion in this volume (Ogg & Pillans, Head et al., Lourens)

At the time of publication discussions concerning the position of the boundary(ies) are at an advanced stage. The formal boundary of the Quaternary/Pleistocene at 1.8 million years is indicated but the proposal to define formally the base of the Quaternary from that of the Pleistocene, at the 2.6 million-year boundary, has already been accepted following formal voting by the ICS. The proposal is awaiting formal ratification by the IUGS. It is expected a decision will be made following the International Geological Congress to be held in Oslo in August 2008.

Similarly there is uncertainty about the status of the term Tertiary (Head et al., this issue). Like the Quaternary, it has often been regarded as a full System/Period (Salvador, 2006a, b) but discussions are in progress on whether the Neogene and Paleogene should be reclassified as sub-systems/sub-periods.

The chart extends to 2.7 million years to include the very end of the preceding Piacenzian Stage of the Pliocene Series.

Pleistocene GSSPs

Formal GSSPs for the Pleistocene Subseries will be proposed in the near future. The INQUA Commission on Stratigraphy/ICS Working Group on Major Subdivision of the Pleistocene agreed to place the Early/Lower–Middle boundary at the Brunhes/Matuyama magnetic reversal Chron boundary (Richmond, 1996). A stratotype locality has yet to be identified, but three candidate sections are being considered by SQS Working Group (Head et al., this issue). Following recent re-evaluation, the Middle–Late/Upper boundary is placed, following historical precedent in NW Europe, at the Saalian–Eemian Stage boundary. The former is positioned at the basal-boundary stratotype of the Eemian in the Amsterdam–Terminal borehole, the Netherlands (Gibbard, 2003; Litt & Gibbard, this issue).

The Holocene is generally regarded as having begun 10,000 radiocarbon years before 1950 AD, or 11.7k calendar years before 2000 AD (Wolff, 2008). This boundary has been defined as a Global Stratotype Section and Point (GSSP; Walker et al., this issue) in the North-GRIP ice core of the Greenland Ice-Core Project (NGRIP: Rasmussen et al., 2006). Auxillary stratotypes are also defined, for example, in an annually-laminated lake sequence in western Germany (Litt et al., 2001).

Marine stage/zone divisions

Isotope studies from the bottom sediments of the world's oceans have indicated that as many as 52 cold and interspersed warm climate periods, often referred to as glacials and interglacials, occurred during the last 2.6 million years. In contrast to the deep sea, continental evidence is so incomplete and regionally variable that terrestrial glacial–interglacial stratigraphies must refer to the ocean record for a global chronological foundation.

Here the deep-sea based, climatically-defined chronostratigraphy is taken from oxygen isotope data collected and processed by Crowhurst (2002), updated by Tzedakis et al. (2006). It is plotted against the magnetostratigraphic time scale prepared and modified from Funnell (1996). The curve plots depict $\delta^{18}O$ (the ratio of ^{18}O versus ^{16}O) in the tests of fossil benthonic (ocean-floor dwelling) foraminifera. Shifts in this ratio are a measure of global ice-volume,

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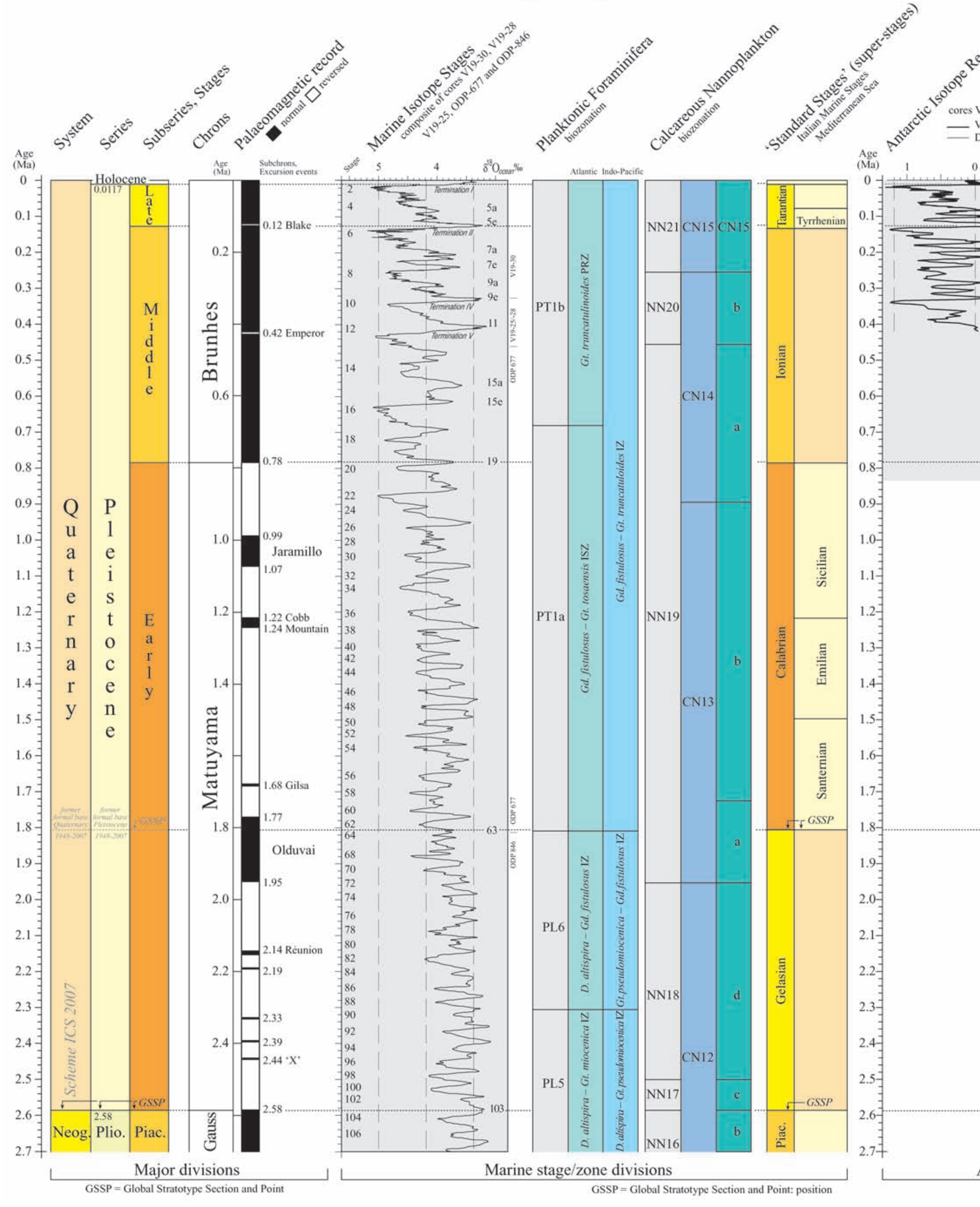

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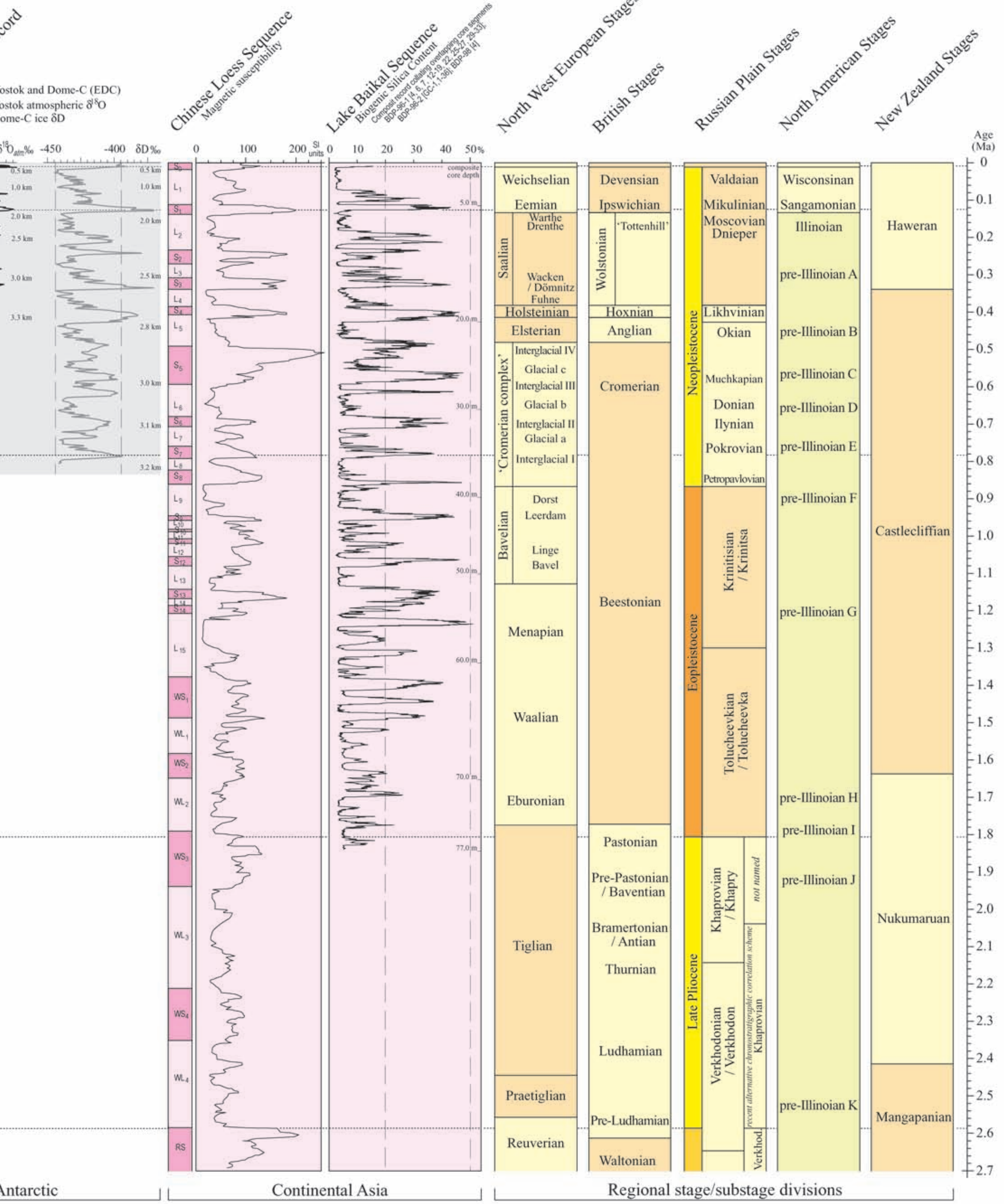

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International Union of Geological Sciences (IUGS), International Commission on Stratigraphy (ICS), Subcommission on Quaternary Stratigraphy (SQS).
http://www.stratigraphy.org/

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which is dependent on global temperature and which determines global sea-level. Planktonic foraminifera and calcareous nannoplankton provide an alternative biostratigraphical means of subdivision of marine sediments. The micropalaeontological zonation is taken from Berggren et al. (1995).

'Standard stage' ('super-stage') global divisions

The desire to divide Quaternary/Pleistocene time into 'standard stages', that is units of approximately the same duration as those in the pre-Quaternary Tertiary time, has been advocated on occasions. The only succession that has been divided in this way is the shallow marine sequences in the Mediterranean region, especially in southern Italy, based principally on faunal and protist biostratigraphy. For various reasons the scheme was considered unsatisfactory for use beyond this region. Renewed investigation in recent years has led to the proposal of units based on multidisciplinary investigation. The Italian shallow marine stages are derived from Van Couvering (1997) modified by Cita et al. (2006 and Cita, this issue).

In view of their duration, encompassing multiple climate cycles and periods for which regional stage units of markedly shorter duration have been defined, these 'standard stages' are considered as 'super-stages'.

Major continental records: Antarctic ice, Chinese Loess, Lake Baikal

Two plots of isotope measurements from Antarctic ice-cores are shown. The first is the 420 ka-long plot from the Vostok core and shows atmospheric $\delta^{18}O$ (Petit et al., 1999), determined from gas bubbles in the ice. This atmospheric $\delta^{18}O$ is inversely related to $\delta^{18}O$ measurements from seawater and therefore is a measure of ice-volume. It can also be used to separate ice volume and deepwater temperature effects in benthic foraminiferal $\delta^{18}O$ measurements. The deuterium measurements (δD) for the last 800 ka are from the 3.2 km deep EDC core in Dome C (EPICA community members, 2004; Jouzel et al., 2007). They come from samples of the ice itself and give a direct indication of Antarctic surface palaeotemperature.

For the Chinese loess deposits the chart shows the sequence of palaeosols (indicated by S and WS) and alternating loess units (L and WL) from Luochuan (An et al., 1990). It is accompanied by a continuous plot of magnetic susceptibility from the same sequence.

The Siberian Lake Baikal provides a bioproductivity record from the heart of the world's largest landmass, an area of extreme continental climate. High concentrations of biogenic silica indicate high aquatic production during interglacials (i.e., lake diatom blooms during ice-free summer seasons). The composite biogenic silica record from cores BDP-96-1, -96-2 and -98 is plotted on an astronomically tuned age scale (Prokopenko et al., 2006). The composite record extends well beyond the top of the Olduvai reversal, a tuned age scale for this part of the series is in preparation.

Regional stage/substage divisions

The continuous sequences, above, provide the comparison for a selection of continental and shallow marine stage-sequences from around the world reconstructed from discontinuous sediment successions. Solid horizontal lines on the plots indicate observed boundaries, where no lines separate stages, additional events may potentially be recognised in the future.

The NW European stages are taken from Zagwijn (1992) and De Jong (1988). The British stages are taken from Mitchell et al. (1973); Gibbard et al. (1991) and Bowen (1999). The Russian Plain stages are taken from the Stratigraphy of the USSR: Quaternary System (1982, 1984), Krasnenkov et al. (1997), Shik et al. (2002), Iossifova (pers. comm.) and Tesakov (pers. comm). In addition, the Russian Pleistocene is also frequently divided into the Eopleistocene, equivalent to the Early Pleistocene Subseries, and the Neopleistocene, equivalent to the Middle and Late Pleistocene Subseries. The North American stages are taken from Richmond (unpublished). The New Zealand stages are from Pillans (1991) and Beu (2004).

Anthropocene

A recent proposal has been made to establish a new series status division following the Holocene, to be termed the *Anthropocene*. The term is being increasingly employed to identify the current interval of anthropogenic global environmental change, and may be adopted on stratigraphical grounds. It might be adopted at formal Series/Epoch level, for the time since the start of the Industrial Revolution when changes sufficient to leave a global stratigraphic signature distinct from that of the Holocene or of previous Pleistocene interglacial phases, occurred. A boundary definition may be made either using a Global Stratigraphic Section and Point ('golden spike') localities, and or by adopting a numerical date (Global Standard Stratigraphic Age: GSSA). Formal adoption of this term depends on its utility, particularly to Earth Scientists working on late Holocene successions (Zalasiewicz et al., 2008). Because of its' short time duration, it has not been included in the chart.

References

Aguirre, E. & Pasini, G. 1985 The Pliocene-Pleistocene boundary: Episodes, 8, pp. 116–120.

An Zhisheng, Lui Tungsheng, Porter, S.C., Kukla, G., Wu Xihao and Hua Yingming 1990 The long-term paleomonsoon variation record by the loess-paleosol sequence in central China: Quaternary International 7/8, pp. 91–95.

Berggren, W.S., Hilgen, F.J., Langereis, C.G., Kent, D.V., Obradovich, J.D., Raffi, I., Raymo, M.E. and Shackleton, N.J. 1995 Late Neogene chronology: new perspectives in high-resolution stratigraphy: Geological Society of America Bulletin, 107, pp. 1272–1287.

Beu, A.G., 2004. Marine mollusca of oxygen isotope stages of the last 2 million years in New Zealand. Part 1: Revised generic positions and recognition of warm-water and cool-water immigrants: Journal of the Royal Society of New Zealand, 34, pp. 111–265.

Bowen, D.Q. 1999. A revised correlation of the Quaternary deposits in the British Isles. Geological Society Special Report no.23.

Bowen, D.Q. & Gibbard, P.L. 2007 The Quaternary is here to stay: Journal of Quaternary Science, 22, pp. 3–8.

Cita, M.B., Capraro, L., Ciaranfi, N., Di Stephano, E., Marino, M., Rio, D., Sprovieri, R. and Vai, G.B., 2006. Calabrian and Ionian: A proposal for the definition of Mediterranean stages for the Lower and Middle Pleistocene: Episodes, 29, pp. 107–113.

Crowhurst, S.J. 2002 Composite isotope sequence. The Delphi project. http://www.esc.cam.ac.uk/new/v10/research/institutes/godwin/body.html.

De Jong, J. 1988: Climatic variability during the past three million years, as indicated by vegetational evolution in northwest Europe and with emphasis on data from The Netherlands. Philosophical Transactions of the Royal Society of London B 318, pp. 603–617.

EPICA members 2004 Eight glacial cycles from an Antarctic ice core: Nature, 429, pp. 623–628.

Funnell, B.W. 1996. Plio-Pleistocene palaeogeography of the southern North Sea Basin. (3.75–0.60 Ma): Quaternary Science Reviews 15, pp. 391–405.

Gibbard, P.L 2003 Definition of the Middle/Upper Pleistocene boundary: Global and Planetary Change, 36, pp. 201–208.

Gibbard, P.L., West, R.G. & Zagwijn, W.H. (editors) 1991 Early and early Middle Pleistocene correlations in the southern North Sea Basin: Quaternary Science Reviews, 10, pp. 23–52.

Gibbard, P.L. Smith, A.G., Zalasiewicz, J.A., Barry, T.L., Cantrill, D., Coe, A.L., Cope, J.C.W., Gale, A.S., Gregory, F.J., Powell, J.H., Rawson, P.R., Stone, P. & Waters, C.N. 2005 What status for the Quaternary?: Boreas, 34, pp. 1–12.

Gibbard, P.L., Cohen, K.M., Boreham, S. & Moscariello, A. 2004. Global chronostratigraphical correlation table for the last 2.7 million years. Subcommission on Quaternary Stratigraphy, International Commission on Stratigraphy: Cambridge.

Gibbard, P.L., Boreham, S., Cohen, K.M. & Moscariello, A. 2005 Global chronostratigraphical correlation table for the last 2.7 million years:Boreas, 34, 1 (inclusion).

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Nouet, J., Barnola, J. M., Chappellaz, J., Fischer, H., Gallet, J. C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schwander, J., Spahni, R., Souchez, R., Selmo, E., Schilt, A., Steffensen, J. P., Stenni, B., Stauffer, B., Stocker, T., Tison, J.-L., Werner, M. and Wolff, E. W. (2007): Orbital and millennial Antarctic climate variability over the last 800,000 years: Science, 317, pp. 793–796

Krasnenkov R.V., Iossifova Yu.I. & Semenov V.V. 1997. The Upper Don drainage basin—an important stratoregion for climatic stratigraphy of the early Middle Pleistocene (the early Neopleistocene) of Russia. Quaternary geology and paleogeography of Russia. Moscow. Geosynthos, pp. 82–96. (Russian; abstract in English).

Litt, T., Brauer, A., Goslar, T., Merkt, K., Balaga, K., Müller, H., Ralska-Jasiewiczowa, M. Stebich, M. & Negendank, J.F.W. 2001 Correlation and synchronisation of lateglacial continental sequences in northern central Europe based on annually laminated lacustrine sediments: Quaternary Science Reviews, 20, pp. 1233–1249.

Mitchell, G.F., Penny, L.F., Shotton, F.W., West R.G. 1973 A Correlation of Quaternary deposits in the British Isles: Geological Society of London Special Report, 4, 99 pp.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delayque, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E. & Stievenard, M. (1999) Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica: Nature, 399, pp. 429–436.

Partridge, T.C. (ed.) 1997a The Plio-Pleistocene boundary: Quaternary International, 40, pp. 1–100.

Partridge, T.C. 1997b Reassessment of the position of the Plio-Pleistocene boundary: is there a case for lowering it to the Gauss-Matuyama Palaeomagnetic reversal? *In*: Partridge, T.C. (ed.) 1997 The Plio-Pleistocene boundary. Quaternary International, 40, pp. 5–10.

Pillans, B. 1991 New Zealand Quaternary stratigraphy: an overview: Quaternary Science Reviews, 10, pp. 405–418.

Pillans, B. and Naish, T., 2004. Defining the Quaternary: Quaternary Science Reviews, 23, pp. 2271–2282.

Prokopenko, A. A., Hinnov, L. A., Williams, D. F., Kuzmin, M. I. 2006 Orbital forcing of continental climate during the Pleistocene: a complete astronomically-tuned climatic record from Lake Baikal, SE Siberia: Quaternary Science Reviews, 25, pp. 3431–3457.

Rasmussen, S. O., Andersen, K.K., Scensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen, H.B., Siggaard-Andersen, M.-L., Johnsen, S.J., Larsen, L.B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R. Fischer, H., Goto-Azuma, K., Hansson, M.E., Ruth, U. 2006. A new Greenland ice core chronology for the last glacial termination: Journal of Geophysical Research, 111. D06102.

Richmond, G.M. 1996 The INQUA-approved provisional Lower-Middle Pleistocene boundary. *In*: Turner C. The early middle Pleistocene in Europe. pp. 319–326, Balkema: Rotterdam.

Rio, D., Sprovieri, R., & Di Stefano, E. 1994 The Gelasian Stage: a proposal of a new chronostratigraphic unit of the Pliocene Series. Rivista Italiano di Paleontoloqia e Stratigrafia 100, 103–124.

Rio, D., Sprovieri, R., Castradori, D., and Di Stefano, E. 1998 The Gelasian Stage (Upper Pliocene): A new unit of the global standard chronostratigraphic scale: Episodes, 91, pp. 82–87.

Salvador, A., 2006a. The Tertiary and the Quaternary are here to stay:AAPG Bulletin, 90, pp. 21–30.

Salvador, A., 2006b. A stable Cenozoic geologic time scale is indispensable: Episodes, v.29, pp.43–45.

Shik S.M., Borisov B.A., Zarrina E.P. 2002 About the project of the interregional stratigraphic scheme of the Neopleistocene of East European Platform and improving regional stratigraphic schemes. The Third All Russian Meeting on the Quaternary research. Abstracts. Geological Institute RAN -Smolensky Pedagogical University. Smolensk. pp. 125–129. (in Russian).

Stratigraphy of the USSR: Quaternary System (1982) volume 1, Moscow. Nedra. 443 pp. (in Russian).

Stratigraphy of the USSR: Quaternary System (1984) volume 2. Moscow. Nedra. 556 pp. (in Russian).

Suc, J.P., Bertini, A., Leroy, S.A.G. & Suballyova, D. 1997 Towards a lowering of the Pliocene/Pleistocene boundary to the Gauss/Matuyama Reversal. *In*: Partridge, T.C. 1997 (ed.) The Plio-Pleistocene boundary. Quaternary International 40, pp. 37–42.

Tzedakis, P.C., Hooghiemstra, H. & Pälike, H. (2006) The last 1.35 million years at Tenaghi Philippon: revised chronostratigraphy and long-term vegetation trends: Quaternary Science Reviews 25, pp. 3416–3430.

van Couvering, J. 1997 Preface, the new Pleistocene. *In*: van Couvering, J. (ed.) The Pleistocene boundary and the beginning of the Quaternary. University Press: Cambridge. ii–xvii.

Wolff, E.W. 2008 What is the "present"?: Quaternary Science Reviews, 26, pp. 3023–2024.

Zagwijn, W.H. 1992, The beginning of the Ice Age in Europe and its major subdivisions. Quaternary Science Reviews 11, pp. 583–591.

Zalasiewicz, J., Smith, A., Williams, M., Barry, T.L., Bown, P.R., Brenchley, P., Cantrill, D., Coe, A.L., Gale,A., Gibbard, P., F. Gregory,J., Hounslow, M., Knox, R., Marshall, J., Oates, M. Powell, J., Rawson, P., Stone, P. & Waters, C. 2008 Are we now living in the Anthropocene?: GSA Today, 18, pp. 4–8.

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The Tertiary: a proposal for its formal definition

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The term Tertiary, subdivided into the Paleogene and Neogene, is traditionally used to represent the interval of geological time between the Cretaceous and Quaternary. In the 1990s, however, the Neogene and Paleogene were ratified by the International Union of Geological Sciences as periods/systems of the Cenozoic Era/Erathem, leaving the Tertiary officially undefined. The Tertiary nonetheless remains a formal term that has never been officially eliminated, and its widespread use today implies a long future. To regularise its use, and following the most widely used topology among Cenozoic time scales, the Tertiary is here proposed as a period/system subjacent to the Quaternary and with its base defined by the Global Stratotype Section and Point that marks the base-Danian Age/Stage at c. 65.5 Ma. The Neogene and Paleogene, currently designated as periods, then become sub-periods within the Tertiary. The top of the Tertiary would be defined by the base of the Quaternary at 2.6 Ma. This proposal complies strictly with the hierarchical requirements of the geological time scale, fully accommodates current proposals by the International Commission on Stratigraphy and International Union for Quaternary Research regarding the Quaternary, and respects the historical and widespread current usage of the term Tertiary.

Introduction

The term Tertiary was originally introduced by Arduino in 1759 as part of his four-fold classification of deposits in the Venetian and Tuscan regions of Italy (Arduino, 1760), and strata he classified as Tertiary are still so regarded today (Vaccari, 2006). The term has been used continuously for more than two hundred years, and affirmed officially by the Paris 1990 International Geological Congress (Vai, 2007). The Tertiary continues to refer to the interval of time between the Cretaceous and Quaternary, and as such is a useful and unambiguous term (Harland et al., 1990) that remains widely used (Salvador, 2006a,b).

The Tertiary is commonly depicted as a period/system in the literature (Salvador, 2006b). However, since 1976, the International Commission on Stratigraphy (ICS) has divided the Cenozoic Era into the Paleogene, Neogene, and Quaternary, treating the Tertiary as a 'useful informal term to include both the Paleogene and Neogene' (Cowie and Bassett, 1989; Figure 1). This was foreshadowed by an earlier recommendation by the Stratigraphy Committee of the Geological Society, London, that the Cenozoic be divided informally into Tertiary and Quaternary sub-eras, with the Tertiary subdivided into Paleogene and Neogene periods/systems (George et al., 1968). This scheme was followed by Curry et al. (1978) and Harland et al. (1982, 1990; Figure 1). Currently, the Cenozoic Era has two formally ratified periods/systems defined by global boundary stratotype sections and points (GSSPs). The Paleogene Period/System was ratified in 1991 by the International Union of Geological Sciences (IUGS) upon acceptance of the basal-Danian GSSP (Molina et al., 2006), and the Neogene Period/System was ratified in 1996 upon the acceptance of the basal-Neogene GSSP (Steininger et al., 1997).

The Tertiary was accordingly absent from the IUGS-sanctioned geological time scales of Cowie and Bassett (1989) and Remane (2000), having been left undefined by the IUGS (Figure 1). The Quaternary was later to experience a similar attempted suppression (Bowen and Gibbard, 2007), although not from the IUGS. In spite of these omissions, the Tertiary has never been explicitly eliminated by the IUGS.

The end of the Tertiary is traditionally defined by the beginning of the Quaternary. The International Union for Quaternary Research (INQUA) and the ICS have recently proposed the Quaternary as a period/system, with its base lowered to the base-Gelasian Age/Stage GSSP at 2.6 Ma. In this proposal, the Gelasian Stage is transferred to the Pleistocene Epoch/Series (Head, Gibbard and Salvador, this issue; and Ogg and Pillans, this issue). It is now timely to assess the rank and duration of the Tertiary. The IUGS has itself acknowledged this need, stating that the Quaternary should be defined with 'due consideration and respect for the issue of the Tertiary' (IUGS correspondence to ICS, May 2007).

Justification of the Tertiary as an official period/system

Sanctioned by long and precise usage, the Tertiary is already a formal stratigraphic term (Salvador, 2006a). It has never been officially eliminated by the IUGS, but its rank and duration have yet to be defined by GSSPs that would regularise its use. Recent proposals have already addressed this issue (Pillans, 2007).

Aubry et al. (2005; Figure 1) proposed the Tertiary and Quaternary as sub-eras/sub-systems, but their scheme is neither acceptable to most Quaternarists nor meets the IUGS's strict requirements of a hierarchical time scale. Walsh (2006) and Salvador (2006a,b) accepted the Tertiary and Quaternary as eras/systems but followed a 1.8 Ma age for the base of the Quaternary, which again is unacceptable to most Quaternarists and to INQUA and the ICS (Head, Gibbard and Salvador, this issue; Ogg and Pillans, this issue).

Berggren (1998) and Luterbacher et al. (2005) argued that the Quaternary and Tertiary should be abandoned because they are part of an obsolete classification. But if names were discarded merely for this reason, we would lose the Cretaceous and Carbonifeous (Walsh, 2006; Vai, 2007). Unlike Primary and Secondary, the terms Quaternary and Tertiary survived because they were useful; and their etymologies are instructive in recalling the early history of stratigraphic research.

In 2005, the ICS recommended that the Tertiary not be considered as a formal division of the geological time scale 'because it is nearly redundant with the entire Cenozoic Era' (International Com-

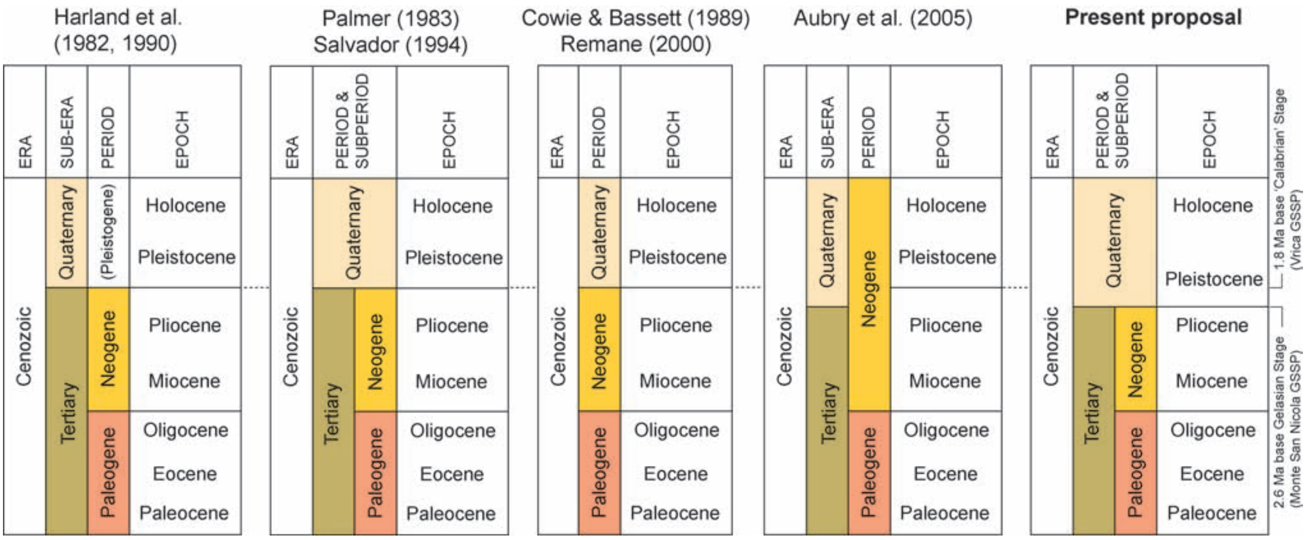

Figure 1 Comparison of Cenozoic time scales. The Palmer (1983) and Salvador (1994) time scale is the most widely accepted Cenozoic time scale in current use (Salvador, 2006b). It is also the preferred option of Walsh (2006, in press), and has been adopted by the US Geological Survey and the Geological Society of America. The time scale by Cowie and Bassett (1989) and Remane (2000) represents the most recent (and current) time scale endorsed by the IUGS. The present proposal adopts the Palmer (1983) and Salvador (1994) time scale except that the Tertiary–Quaternary boundary is lowered to 2.6 Ma in accordance with Head, Gibbard and Salvador (this issue) and Ogg and Pillans (this issue). Intervals of geological time are not to scale.

mission on Stratigraphy, 2005, p. 2–3). But this argument would also apply to the Pleistocene, whose duration almost fully overlaps with the Quaternary (Walsh, 2006). Moreover, the Tertiary has terminated whereas the Cenozoic (and for that matter the Holocene) is ongoing.

The term Tertiary remains used more frequently in stratigraphic publications than either Paleogene or Neogene (Salvador, 2006 a, b). Tertiary already appears as a period/system in the vast majority of published time scales, where it is typically subdivided into Paleogene and Neogene sub-periods/sub-systems (Salvador, 2006b). Its use in the literature has not declined in the past 25 years; and its continued use as a period/system by the Geological Society of America, US Geological Survey (U.S. Geological Survey Geologic Names Committee, 2007), and by individual U.S. state and other national geological surveys, illustrates its wide currency (Salvador, 2006a). It is noteworthy that the term Tertiary, and its abbreviation in 'K/T boundary', appears throughout the very publication (Molina et al., 2006) that ostensibly suppresses its name. Moreover, it is ironic that the Quaternary, not the Tertiary, should have survived on IUGS-approved time scales, when the Quaternary was the least well treated of Arduino's four orders (Vaccari, 2006).

Proposal to establish the Tertiary as a GSSP-defined period/system

For the above reasons, and to maintain stability within the Cenozoic time scale, we propose that the Tertiary be treated as an official period/system contiguous with, and subjacent to, the Quaternary Period/System, with its base defined by the GSSP near El Kef, Tunisia. This GSSP already defines the base of the Danian Stage (c. 65.5 Ma; Molina et al., 2006). The Cenozoic, Quaternary, Paleogene and Danian are thus coterminous. In our proposal (Figure 2), the Paleogene and Neogene become sub-periods/sub-systems of the Tertiary, just as the Mississippian and Pennsylvanian enjoy popular use as sub-periods/sub-systems of the Carboniferous. In our scheme, the top of the Tertiary Period/System is defined by the base of the Quaternary Period/System, Pleistocene Epoch/Series, and Gelasian Age/Stage, all of which would share the same GSSP at the base-Gelasian dated at 2.588 Ma (Rio et al., 1998). As a technicality, this would require de-ratifying the Paleogene and Neogene as periods/systems, and re-ratifying them as sub-periods/sub-systems.

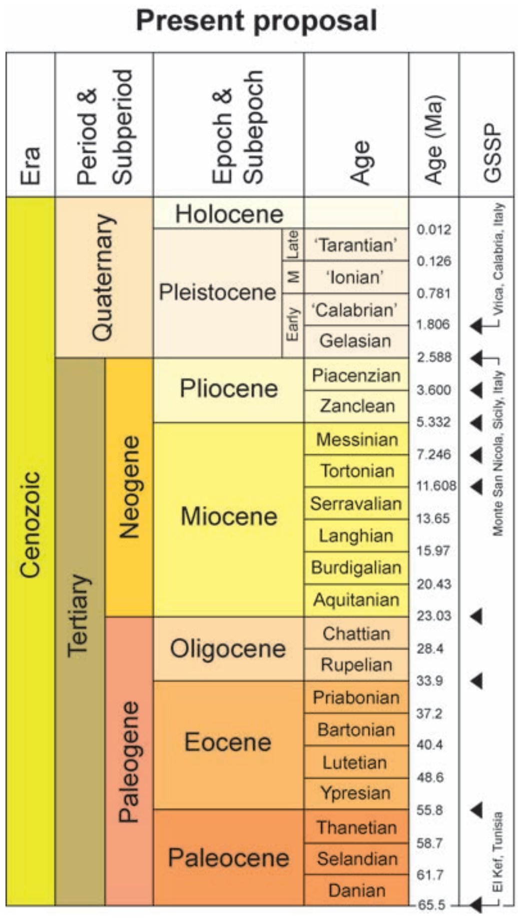

Figure 2 The present proposal for the Cenozoic time scale. Age names and boundary ages are from the ICS website in January 2008, with the provisional Calabrian and Ionian ages following Cita et al. (2006) and the provisional Tarantian Age following Cita (this issue, and references therein). Currently defined GSSPs are indicated by black triangles. Only those GSSPs mentioned in the text are labeled. Intervals of geological time are not to scale.

The duration of the Tertiary (62.9 Myr) is similar to that of many other periods in the time scale. The Quaternary (2.6 Myr), while obviously shorter, is ongoing. Our proposed scheme (Figure 2) follows the most popular and widely used topology (e.g., Palmer, 1983; Salvador, 1994, 2006a, b; Walsh, 2006, Figure 1B) while accepting the justification for placing the Tertiary–Quaternary boundary at 2.6 Ma (Head, Gibbard and Salvador, this issue; Ogg and Pillans, this issue). Our scheme meets the IUGS requirements of a hierarchical time scale, requires no unusual designations of rank, and respects historical precedents and established usage of the term Tertiary.

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References

Arduino, G., 1760, Sopra varie sue Osservazioni fatte in diverse parti del Territorio di Vicenza, ed altrove, appartenenti alla Teoria Terrestre, ed alla Mineralogia. Letter to Prof. Antonio Vallisnieri, dated 30th March, 1759. Nuova Raccolta di Opuscoli Scientifici e Filologici (Venice), v. 6 (1760).

Aubry, M.-P., Berggren, W.A., Van Couvering, J., McGowran, B., Pillans, B., and Hilgen, F., 2005. Quaternary: status, rank, definition, survival: Episodes, v. 28, pp. 118–120.

Berggren, W.A., 1998. The Cenozoic Era: Lyellian (chrono)stratigraphy and nomenclatural reform at the millennium. *In*: Blundell, D.J., and Scott, A.C. (eds), Lyell: the past is the key to the present: Geological Society, London, Special Publication, 143, pp. 111–132.

Bowen, D.Q., and Gibbard, P.L., 2007. The Quaternary is here to stay: Journal of Quaternary Science, v. 22, pp. 3–8.

Cita, M.B., Capraro, L., Ciaranfi, N., Di Stefano, E., Marino, M., Rio, D., Sprovieri, R., and Vai, G.B., 2006. Calabrian and Ionian: A proposal for the definition of Mediterranean stages for the Lower and Middle Pleistocene: Episodes, v. 29, 107–114.

Cowie, J.W. and Bassett, M.G. (compilers) 1989. 1989 global stratigraphic chart with geochronometric and magnetostratigraphic calibration: Episodes, 12 (2), supplement, 1 sheet.

Curry, D., Adams, C.G., Boulter, M.C., Dilley, F.C., Eames, F.E., Funnell, B.M., and Wells, M.K., 1978. A correlation of Tertiary rocks in the British Isles: Geological Society, London, Special Report 12, 72 pp.

George, T.N. and 12 others, 1968. International Geological Correlation Programme—United Kingdom contribution—Recommendations on stratigraphical classification: The Royal Society, London, 43 pp.

Harland, W.B., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G., and Walters, R., 1982. A geologic time scale: Cambridge University Press, Cambridge, i–xi, pp.1–131.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., and Smith, D.G., 1990. A geologic time scale 1989: Cambridge University Press, Cambridge, i–xvi, pp.1–263.

Head, M.J., 2007. Tracking the status and duration of the Quaternary – a resolution in sight? CANQUA Annual Meeting: Carleton University, Ottawa, June, 2007.

International Commission on Stratigraphy, 2005. Definition and rank of Quaternary. Unpublished report to the IUGS, 9 pp. (available online at: *http://www.stratigraphy.org/*).

Luterbacher, H.P., Ali, J.R., Brinkhuis, H., Gradstein, F.M., Hooker, J.J., Monechi, S., Ogg, J.G., Powell, J., Röhl, U., Sanfilippo, A., and Schmitz, B., 2005. The Paleogene Period. *In*: Gradstein, F.M., Ogg, J.G., and Smith, A.G. (eds.), A Geologic Time Scale 2004: Cambridge University Press, Cambridge, pp. 384–408 [Imprinted 2004].

Molina, E., Alegret, L., Arenillas, I., Arz, J.A., Gallala, N., Hardenbol, J., von Salis, K., Steurbaut, E., Vandenberghe, N., and Zaghbib-Turki, D., 2006. The Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene, "Tertiary", Cenozoic) at El Kef, Tunisia: Episodes, v. 29, pp. 263–273.

Palmer, A.R. (compiler) 1983. The Decade of North American Geology 1983 geologic time scale: Geology, v.11, pp. 503–504.

Pillans, B., 2007. Defining the Quaternary: Where do we go from here?: Stratigraphy, v. 4, pp. 145–149.

Remane, J. (compiler) 2000. International Stratigraphic Chart. International Union of Geological Sciences, and UNESCO Division of Earth Sciences, Paris.

Rio, D., Sprovieri, R., Castradori, D. and Di Stefano, E., 1998. The Gelasian Stage (Upper Pliocene): A new unit of the global standard chronostratigraphic scale: Episodes, v. 21, pp. 82–87.

Salvador, A. (ed.), 1994. International Stratigraphic Guide, second edition: International Union of Geological Sciences, and The Geological Society of America, Inc., Boulder Colorado, i–xix, pp. 1–214.

Salvador, A., 2006a. The Tertiary and the Quaternary are here to stay: AAPG Bulletin, v. 90, pp. 21–30.

Salvador, A., 2006b. A stable Cenozoic geologic time scale is indispensable: Episodes, v. 29, pp. 43–45.

Steininger, F.F., Aubry, M.P., Berggren, W.A., Biolzi, M., Borsetti, A.M., Cartlidge, J.E., Cati, F., Corfield, R., Gelati, R., Iaccarino, S., Napoleone, C., Ottner, F., Rögl, F., Roetzel, R., Spezzaferri, S., Tateo, F., Villa, G., and Zevenboom, D., 1997. The global stratotype section and point (GSSP) for the base of the Neogene: Episodes, v. 20, pp. 23–28.

U.S. Geological Survey Geologic Names Committee, 2007. Divisions of geologic time—Major chronostratigraphic and geochronologic units: U.S. Geological Survey Fact Sheet 2007–3015, 2 p.

Vaccari, E., 2006. The "classification" of mountains in eighteenth century Italy and the lithostratigraphic theory of Giovanni Arduino (1714–1795): Geological Society of America Special Paper 411, pp. 157–177.

Vai, G.B., 2007. A history of chronostratigraphy: Stratigraphy, v. 4, pp. 83–97.

Walsh, S.L., 2006. Hierarchical subdivision of the Cenozoic Era: A venerable solution, and a critique of current proposals: Earth-Science Reviews, v. 78, pp. 207–237.

Walsh, S.L., in press. The Neogene: origin, adoption, evolution, and controversy: Earth-Science Reviews.

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by Maria Bianca Cita

Summary of Italian marine stages

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Eight marine stages for the Quaternary have been defined in Italy starting from 1872 (Sicilian of Doderlein) to 1979 (Selinuntian of Ruggieri and Sprovieri). The definition of all these stages was based essentially on invertebrate paleontology, initially from the study of pelecypods and gastropods, but also of corals, ostracods, benthic foraminifers and, more recently, on planktonic foraminifers and calcareous nannofossils. The 1948 International Geological Congress held in London decided to search for a locality in Italy to define the Neogene/Quaternary boundary in correspondence with the first appearance of the "northern guests" in the Mediterranean. The Vrica section of Calabria was selected for defining the GSSP of the Pleistocene in 1984.

Meanwhile, starting from 1970 the deep-sea record of the western, central and eastern Mediterranean was explored by five Legs of the Deep Sea Drilling Program and Ocean Drilling Program. As a result of integrated, high resolution multidisciplinary investigations of the deep-sea record and of continuous sections exposed on land, a robust chronostratigraphic framework could be constructed. The combination of biochronology, magnetostratigraphy, isotopic stratigraphy, astrocyclostratigraphy, and tephrostratigraphy assures the worldwide correlation potential of the Mediterranean record.

Original definitions

The sedimentary successions of Quaternary age, particularly of marine facies, are so expanded, well exposed and richly fossiliferous in Italy, that they were well known since the times when Lyell (1833) considered the Newer Pliocene (now Pleistocene) as the unit more similar to the Present, because 90 to 95% of the taxa recovered from that time interval were still living in the present seas. The best outcrops, whose molluscan faunas were described by Brocchi (1809, 1814), are located on the lower slopes of the Apennines facing the Po Plain. Other fossiliferous exposures that attracted the attention of the scientists for the definition of new stages in the 19th and 20th centuries lie in the southernmost part of the Italian peninsula, in Sicily and in Sardinia.

The marine stages that have been defined in Italy are as follows, in chronological order:

Sicilian (Doderlein, 1872)
Calabrian (Gignoux, 1910)
Tyrrhenian (Issel, 1914)
Milazzian (Dépéret, 1918)
Emilian (Ruggieri & Selli, 1949)
Santernian (Ruggieri & Sprovieri, 1975)
Crotonian (Ruggieri et al., 1977)
Selinuntian (Ruggieri & Sprovieri, 1979).

The definition of all these stages was based essentially on invertebrate paleontology, initially from the study of pelecypods and gastropods, but also of corals, ostracods, benthic foraminifers and, more recently, on planktonic foraminifers and calcareous nannofossils. The Selinuntian Stage was proposed as a superstage replacing the Calabrian, and included from bottom to top the Santernian, characterized by a cold-water fauna, the temperate Emilian and the Sicilian, indicative of very cold conditions. Measured sections, carefully described, are to be found in Gignoux's monograph (1913) but are seldom recorded elsewhere. This notwithstanding several Italian stages have been, and still are reported in various time scales with special reference to the Calabrian, Sicilian and Tyrrhenian.

Meanwhile, the 1948 International Geological Congress held in London decided to search for a locality in Italy to define the Neogene/Quaternary boundary in correspondence with the first appearance of the "northern guests" in the Mediterranean. In 1974 IGCP launched Project 41 (Neogene/Quaternary boundary) with Nikiforova as Project leader, and soon after Selli et al. (1977) proposed the Vrica section in Calabria as a potential Neogene/Quaternary-stratotype. The 1982 INQUA Congress, held in Moscow, decided to locate the Neogene /Quaternary boundary at the top of the Olduvai subchron as expressed in the Vrica section at the level of sapropel "*e*". No mention was made of the Calabrian stage in the various documents, so that its use declined.

Further developments

None of the stages listed above meets the prescriptions of the International Commission on Stratigraphy and of the International Stratigraphic Guide (Hedberg, 1976; Cowie, l986; Remane et al., 1996) so that they were considered as *nomina nuda* (Vai, 1996). A revision was undertaken in 1990 under the auspices of the Italian Commission on Stratigraphy, as reported in Cita et al. (Episodes, in press) to which reference is made here. After a joint visit to all the sections described in the literature in Sicily and Calabria, attention was concentrated on the Vrica section for the Calabrian, on the Valle di Manche section also from Calabria, and on a coeval section better exposed, more expanded and open marine, from the core of the Apennine foredeep in Basilicata for the post-Calabrian interval. These sections have been investigated with an integrated stratigraphy approach, using all the techniques available, with biochronology as a first (unidirectional) approach, followed by paleomagnetic stratigraphy, isotopic stratigraphy, tephrostratigraphy, and astrocyclostratigraphy as appropriate.

Meanwhile, the deep sea record of the western, central and eastern Mediterranean was explored by the Deep Sea Drilling Program (DSDP Legs 13 and 42A) and of the Ocean Drilling Program (Legs 107, 160 and 161). Continuous coring with full recovery was accomplished throughout the Plio-Pleistocene interval in the Tyrrhenian, Balearic, Ionian and Levantine basins (Figure 1), and the detailed studies based on the material recovered served for the definition of biochronologic schemes (Cita, 1975; Rio et al.,1990 inter alias).The eastern Mediterranean, in particular, is of paramount importance because of its peculiar paleogeographic and paleoceanographic situation that results in a highly resolved, unique lithostratigraphic succession with hemipelagic marls as dominant lithology, sapropels and

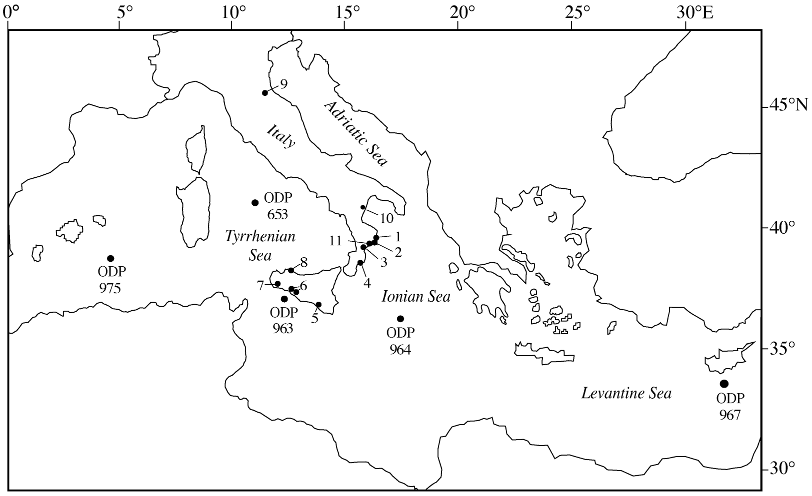

Figure 1 Location of the stratigraphic sections and of DSDP/ODP drillsites mentioned in the text.

tephras as minor, isochronous lithologies. Indeed, sapropels are the sedimentary expression of basin-wide stagnation whereas tephras result from explosive volcanic activity, which is quite frequent due to the presence of two active volcanic arcs in the area. Astrocyclostratigraphy was first applied to these successions starting from the nineties (Hilgen, 1991; Lourens et al., 1996), (see Figure 2).

Summary of present situation

As of the end of 2007, the CALABRIAN stage has been redefined (Cita et al., in press; see also Cita et al., 2006) with the Vrica section as type section, and three auxiliary sections on land, plus a deep-sea auxiliary section (unit stratotype sensu Hilgen et al., 2006).

In the Vrica section the GSSP is defined at the top of sapropelic level "*e*" (primary marker). Secondary markers are considered the position of the GSSP above the last occurrence of *Discoaster brouweri* and of *Globigerinoides obliquus extremus*, below the first occurrence of medium-sized *Gephyrocapsa* and of *Globigerinoides tenellus*, and in coincidence with the first increase in abundance of left coiling *Neogloboquadrina pachyderma*. The Vrica GSSP falls about 10 m below the top of the Olduvai subchron and is correlatable with the top of Marine Isotopic Stage (MIS) 65.

The first two on-land auxiliary sections are that of Singa in Calabria and that of Capo Rossello in Sicily (see Figure 3 and Cita et al., in press). Both these sections duplicate the lower part of the Calabrian, and extend from MIS 65 to MIS 50 or 49, whereas the upper portion of the Vrica section extends up to MIS 37. In other words, the Vrica section does not encompass the entire interval from approximately 1.8 to 0.78 Ma but terminates at about 1.2 Ma. The upper part of the Calabrian (see location in Figure 1 and columnar logs with biohorizons in Figure 3) is expressed in the Montalbano section of Basilicata that extends from MIS 37 to MIS 16. The Montalbano section is the third auxiliary section for the Calabrian stage. As a deep-sea reference, the Ionian Sea ODP Site 964 is indicated. All the criteria used, including astrocyclostratigraphy and tephrostratigraphy, allow a precise chronocorrelation.

The IONIAN encompasses the interval from approximately 0.78 Ma to approximately 0.13 Ma (from the Matuyama/Brunhes reversal within MIS 19 to the MIS 6/5 boundary or Termination II) and is represented by two sections, that of Valle di Manche in Calabria (Rio et al., 1996; Massari et al., 2002; Capraro et al., 2005) and that of Montalbano in the core of the Apennine foredeep (Cita and Castradori, 1994; Ciaranfi et al., 2000; Ciaranfi and D' Alessandro, 2000; Ciaranfi et al., submitted). Both are suitable for the purpose of identifying the lower boundary and have been investigated in great detail in the last several years. They can be chronocorrelated by means of multiple techniques, including calcareous nannofossil biochronology, palynology, isotopic stratigraphy and tephrostratigraphy. The only advantage of the first is that the magnetostratigraphy is well known, whereas weathering of the well exposed badlands has prevented, until recently, the development of a magnetostratigraphy in the much more expanded Montalbano section, which is 480 m thick and encompasses all the MIS stages from 37 to 16 (see Ciaranfi et al., submitted). A paleomagnetic study of the Montalbano section is currently in progress (N. Ciaranfi pers. comm. 2007). A perfect auxiliary section in the open sea is represented by ODP Site 963 offshore Capo Rossello. At a water depth of 480 m, it lies at a distance of a few miles from the "Rossello composite" section, that includes the GSSP of the Zanclean and Piacenzian stages and the correlative levels of the Gelasian and Calabrian GSSPs. Multiple coring to the final depth of 206 m subbottom encountered the Matuyama/Brunhes magnetic reversal at 155 m subbottom and the Jaramillo subchron at 170 m. The entire succession is devoid of turbidites and has been deposited at a high sedimentation rate, ideally suited for high resolution investigations (see Di Stefano, 1998; Sprovieri et al., 2003; Sprovieri et al., 2006).

TARANTIAN is the name proposed over ten years ago (Cita & Castradori, 1994, 1995; van Couvering, 1995) for the interval from the MIS 6/5 boundary (0.13 Ma) or Termination II, to the Holocene in substitution of the well known and widely accepted Tyrrhenian. The original definition by Issel (1914) was based on a rich fossil

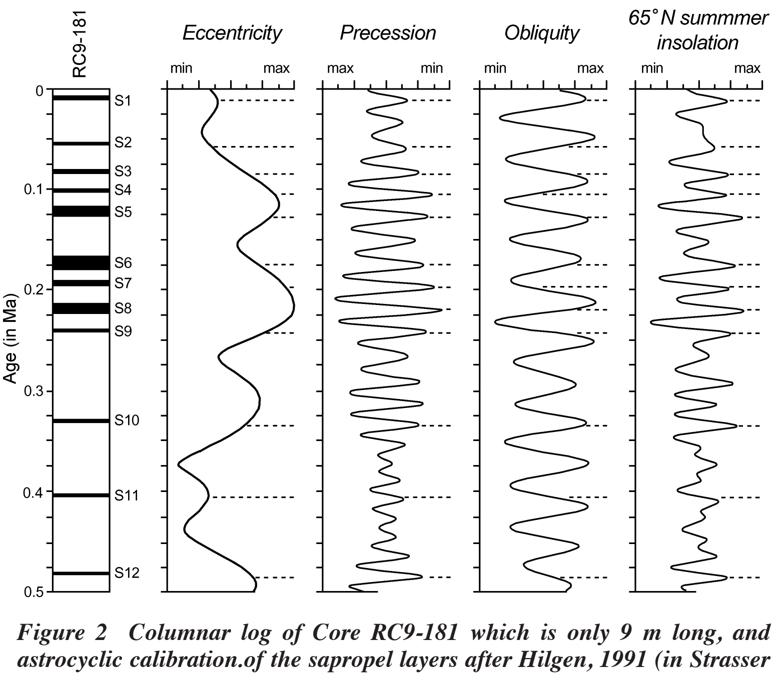

Figure 2 Columnar log of Core RC9-181 which is only 9 m long, and astrocyclic calibration.of the sapropel layers after Hilgen, 1991 (in Strasser et al., 2006). The MIS 6/5 boundary (Termination II) is recorded immediately underneath sapropel S 5, a marker horizon easily identified in all the eastern Mediterranean deep-sea cores, while the MIS 2/1 boundary (Termination I) is recorded underneath sapropel S 1.

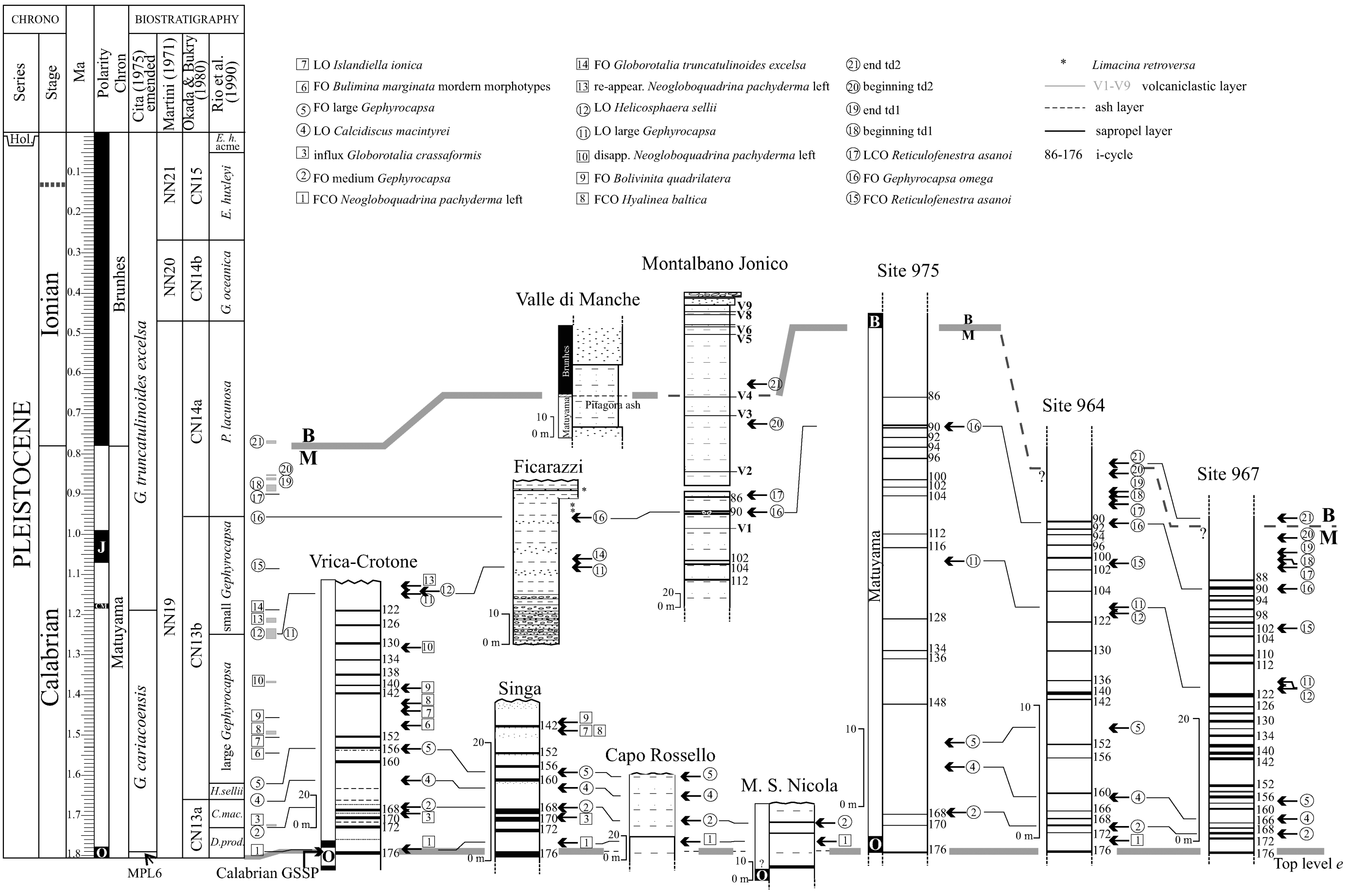

Figure 3 Biochronologic and paleomagnetic correlation of the sections investigated with multiple techniques for the definition of the Calabrian and Ionian stages from the land record and from the deep-sea record.

fauna indicative of tropical conditions with *Strombus bubonius, Conus testudinarius, Patella ferruginea, Cladocora cespitosa* recorded in raised terraces from several localities around the gulf of Cagliari. But Issel's definition of the Tyrrhenian stage indicated the time interval postdating the Sicilian (of Doderlein, 1872) and predating the Holocene, which in those days (pre-Milankovitch's theory) was conceived as the time that terminated the Neolithic age and caused the extinction of large carnivors in Europe. These criteria are still acceptable today. In other words, the Tyrrhenian included not only the sedimentary expression of the warmest interval of the Pleistocene, that in stable passive margin settings may be represented by just an erosional notch, or by *Strombus* raised beaches, but also included the last two glaciations. Long excruciating discussions among geomorphologists and marine stratigraphers on the advantages versus disadvantages of keeping an old well rooted name (see Cita et al., 2005) versus introducing a new term resulted in the proposition of the Tarantian. The reason for substituting Tarantian for the well known Tyrrhenian is essentially conceptual more than factual. Indeed the name Tyrrhenian has been commonly and consistently associated with a “warm” interval.

Investigations on the Tarantian, by a large multidisclinary group, are presently very active under the leadership of Fabrizio Antonioli, who presented the state-of the art at the XVIIth INQUA Congress in Cairns, Australia in August 2007. The proposed type section is in the Mare Piccolo di Taranto, is several meters thick, contains richly fossiliferous beach rocks with *Strombus* and *Cladocora cespitosa,* suitable for radiometric age determinations. Unlike other late Pleistocene nearshore exposures, the fossiliferous deposits unconformably overlie marine marls of mid Pleistocene age.

Selected references

Brocchi, G.B., 1809, Conchiologia fossile subappennina con osservazioni geologiche sugli Appennini e sui suoli adiacenti. Giovanni Silvestri, Milano, 1, pp. 1–430.

Brocchi, G.B., 1814, Conchiologia fossile subappennina. Giovanni Silvestri, Milano, 2, pp. 1–556.

Capraro, L., Asioli, A., Backman, J., Bertoldi, R., Channell, J.E.T., Massari, F., and Rio, D., 2005, Climatic patterns revealed by pollen and oxygen isotope records across the Matuyama/Brunhes Boundary in central Mediterranean (Southern Italy): Geological Society of London, Special Publications, v. 247, pp. 159–182.

Ciaranfi, N., Lirer, F., Pelosi N., Lourens, L.J., Maiorano, P., Marino, M., Stefanelli, S., Brilli, M., and Joannin, S., 2007, Astronomical calibration of Mediterranean Montalbano Jonico land section and implication for $\delta^{18}O$, calcareous nannofossil and tephra records at the Mid-Pleistocene revolution: Terranova (submitted).

Ciaranfi, N., D'Alessandro, A., Girone, A., Maiorano, P., Marino, M., Soldani, D., and Stefanelli, S., 2001, Pleistocene sections in The Montalbano Jonico area and the potential GSSP for Early-Middle Pleistocene in the Lucania Basin (Southern Italy), in Ciaranfi, N., Pasini, G., and Rio, D., eds, The meeting on the Plio/Pleistocene boundary and the Lower/Middle Pleistocene transition: type areas and sections (Bari, 25–29 Sseptember 2000): Memorie di Scienze Geologiche, v. 53, pp. 67–83.

Ciaranfi, N., and D'Alessandro, A., 2005, Overview of the Montalbano Jonico area and section: a proposal for a boundary stratotype for the lower-middle Pleistocene, Southern Italy Foredeep: Quaternary International, v. 131, pp. 5–10.

Cita, M. B., 1975, Planktonic foraminiferal biozonation of the Mediterranean Pliocene deep sea record. A revision: Rivista Italiana di Paleontologia e Stratigrafia, v. 81,. pp. 527–544.

Cita, M. B., Capraro, L., Ciaranfi, N., Di Stefano, E., Marino, M., Rio, D., Sprovieri, R., and Vai, G. B., 2006, Calabrian and Ionian: A proposal for the definition of Mediterranean stages for the Lower and Middle Pleistocene: Episodes, v. 29, no. 2, pp. 159–182.
Cita, M. B., Capraro, L., Ciaranfi, N., Di Stefano, E., Lirer F., Maiorano P., Marino, M., Raffi I., Rio, D., Sprovieri, R., Stefanelli S., and Vai, G. B., 2007, The Calabrian Stage redefined: Episodes, in press.
Cita, M.B., and Castradori, D., 1994, Workshop on marine sections of Gulf of Taranto (Southern Italy) usable as potential stratotypes for the GSSP of the Lower, Middle and Upper Pleistocene: Il Quaternario, v. 7, pp. 677–692.
Cita, M.B., and Castradori, D., 1995, Rapporto sul Workshop "Marine sections from the Gulf of Taranto (Southern Italy) usable as potential stratotypes for GSSP of the Lower, Middle and Upper Pleistocene": Bollettino della Società Geologica Italiana, v.114, pp. 319–336.
Cita, M.B., Capotondi, L., and Asioli, A., 2005, The Tyrrhenian stage in the Mediterranean: definition, usage and recognition in the deep-sea record. A proposal: Rendiconti Accademia Nazionale dei Lincei, s. 9, v. 16, pp. 297–310
Cowie, J.W., 1986, Guidelines for boundary stratotypes: Episodes, v. 9, no. 2, pp.78–82.
Dépéret, C., 1918, Essai de coordination chronologique des temps quaternaires. Comptes Rendus de l'Academie des Sciences, v. 166, 12, pp. 480–486, Paris.
Di Stefano, E., 1998, Calcareous nannofossil quantitative biostratigraphy of Holes 969E and 963B (Eastern Mediterranean). in Robertson, A.H.F., Emeis, K.C., Richter, C. and Camerlenghi, A., eds, Proceedings of the Ocean Drilling Program, Scientific Results, v. 160, pp. 99–112. College Station, TX (Ocean Drilling Program).
Doderlein, P., 1872, Note illustrative della carta geologica del Modenese e del Reggiano: Memoria III, pp. 74.
Gignoux, M., 1910, Sur la classification du Pliocène et du Quaternarie dans l'Italie du Sud: Comptes: Rendus de l'Academie des Sciences, v. 150, pp. 841–844, Paris.
Gignoux, M., 1913, Les formations marine Pliocènes et Quaternaires dans Italie du Sud et la Sicile: Annales Université de Lyon, n.s., v. 36, pp. 1–633.
Hedberg, D.H., 1976, International Stratigraphic Guide–A guide to stratigraphic classification, terminology and procedure: John Wiley and Sons, New York, pp. 1–200.
Hilgen, F.J., 1991, Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the Geomagnetic Polarity Time Scale: Earth and Planetary Science Letters, v. 104, pp. 226–244.
Hilgen, F.J., Brinkhuis, H., and Zachariasse, W.J., 2006, Unit stratotypes for global stages: The Neogene perspective: Earth-Science Reviews, v. 74, pp. 113–125.
Issel, A., 1914, Lembi fossiliferi quaternari e recenti nella Sardegna meridionale dal prof. D. Lovisato: Rendiconti Accademia Nazionale dei Lincei, s. 5, v. 23, pp. 759–770.
Lourens, L.J., Antonarakou, A., Hilgen, F.J., Van Hoof, A.A.M., Vergnaud-Grazzini, C., and Zachariasse, W., 1996, Evaluation of the Plio-Pleistocene astronomical timescale: Paleoceanography, v. 11, pp. 391–413.
Lyell, C., 1833, Principles of Geology, v. 3, John Murray, London, 398 pp.
Massari, F., Rio, D., Sgavetti, M., Prosser, G., D'Alessandro, A., Asioli, A., Capraro, L., Fornaciari, E., and Tateo, F., 2002, Interplay between tectonics and Glacio-eustasy, Pleistocene of the Crotone Basin, Calabria (southern Italy): Bulletin of the American Geological Society, v. 114, pp. 1183–1209.
Remane, J., Bassett, M.G., Cowie, J.W., Gohrbandt, K.H., Lane, H.R., Michelsen, O., and Naiwen, W., 1996, Revised guidelines for the establishment of global chronostratigraphic standards by the International Commission on Stratigraphy (ICS): Episodes, v. 19, pp. 77–81.
Rio, D., Channell, J.E.T., Massari, F., Poli, M.S., Sgavetti, M., D'Alessandro, A., and Prosser, G.,eustasy, 1996, Reading Pleistocene euastasy in a tectonically active siliciclastic shelf setting (Crotone peninsula, southern Italy): Geology, v. 24, pp. 743–746.
Rio, D., Raffi, I., and Villa, G., 1990, Pliocene-Pleistocene calcareous nannofossil distribution patterns in the Western Mediterranean, *in* Kastens, K.A., Mascle, J., et al. eds, Proceedings of the Ocean Drilling Program, Scientific Results, v. 107, pp. 513–532. College Station, TX (Ocean Drilling Program).
Ruggieri, G., and Selli, R., 1949, Il Pliocene ed il Post Pliocene dell'Emilia: Giornale di Geologia (2), v. 20, pp. 1–14.
Ruggieri, G., and Sprovieri, R., 1975, La definizione dello stratotipo del Piano Siciliano e le sue conseguenze: Rivista. Minereraria. Siciliana, v. 26, pp. 151–153.
Ruggieri, G., and Sprovieri, R., 1979, Selinuntiano, nuovo superpiano per il Pleistocene inferiore: Bollettino della Società Geologica Italiana, v. 96, pp. 797–802.
Ruggieri, G., Unti, A., Unti, M., and Moroni, M. A., 1977, La calcarenite di Marsala (Pleistocene inferiore) e i terreni contermini: Bollettino della Società Geologica Italiana, v. 74, pp. 1623–1657.
Selli, R., Accorsi, C.A., Bandini Mazzanti, M., Bertolani Marchetti, D., Bonadonna, F.P., Borsetti, A.M., Cati, F., Colalongo, M.L., d'Onofrio, S., Landini, W., Menesini, E., Mezzetti, R., Pasini, G., Savelli, G., and Tampieri, R., 1977, The Vrica section (Calabria). A potential Neogene-Quaternary boundary stratotype: Giornale di Geologia, v. 41, pp. 181–204.
Sprovieri, R., Di Stefano, E., Incarbona, A., and Gargano, M.E., 2003, A high resolution record of the last deglaciation in the Sicily Channel based on foraminifera and calcareous nannofossil quantitative distribution: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 202, pp. 119–142.
Sprovieri, R., Di Stefano, E., Incarbona, A., and Oppo, W.D., 2006, Suborbital climate variability during Marine Isotopic Stage 5 in the central Mediterranean basin: evidence from calcareous plankton record: Quaternary Science Reviews, v. 25, pp. 2332–2342.
Strasser, A., Hilgen, F.J., Heckel, P.H., et al., 2007, Ciclostratigraphy – concepts, definitions, and applications: Newsletters on Stratigraphy, v. 42, 2, pp. 75–114.
Vai, G.B., 1996, Revisione critico-storica dei piani marini del Quaternario: Servizio Geologico Italiano, Miscellanea, VI, pp. 1–179.
Van Couvering, J.A., 1995, Setting Pleistocene Marine Stages: Geotimes, v. 40, pp. 10–11.

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by Martin J. Head[1], Brad Pillans[2], and Sarah A. Farquhar[3]

The Early–Middle Pleistocene Transition: characterization and proposed guide for the defining boundary

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The mid-Pleistocene transition (MPT, c. 1.2 to 0.5 Ma) records fundamental changes in Earth's climate state, where low-amplitude 41-kyr obliquity-dominated cycles gave way progressively to the high-amplitude, quasi-periodic (c. 100-kyr) fluctuations that characterize the later Pleistocene and Holocene. We use wavelet analysis on the LR04 $\delta^{18}O$ benthic foraminiferal stack to confirm low-frequency power as early as 1.25–1.20 Ma, determine the persistence of obliquity-dominated cyclicity through and beyond the MPT, and reveal new levels of complexity in climate evolution. Beginning around 900 kyr, successive major glaciations, most notably in the northern hemisphere, profoundly affected the biota and physical environment. The Matuyama–Brunhes palaeomagnetic Chron boundary (c. 773 ka) is close in age to a major glacial event, occurs approximately at the middle of the MPT, and is widely identified in marine and terrestrial deposits. It would serve as the best overall guide for the Early–Middle Pleistocene Sub-series/Sub-epoch boundary.

Introduction

The mid-Pleistocene transition (MPT, c. 1.2–0.5 Ma) is widely recognized in both marine and continental strata as marking a major global climatic reorganization that profoundly affected ocean and atmospheric circulation, ice sheets and the distribution and evolution of biota, including the ancestors of modern humans (Figure 1). During this transition, low-amplitude 41-ka obliquity-driven climatic cycles of the earlier Pleistocene were progressively overshadowed by quasi-periodic, low frequency (c. 100 kyr) fluctuations in the later Pleistocene. This low-frequency cyclicity was driven by precessional forcing (23 kyr period), with each cycle defined by the fourth or fifth precessional cycle (Maslin and Ridgwell, 2005), and is characterized by a succession of severe glacial episodes particularly in the northern hemisphere.

Orbital forcing parameters do not vary significantly across the MPT, implying that non-linear internal feedbacks in the Earth climate system are responsible for the transition. The pronounced asymmetrical 'saw-tooth' pattern of climate cycles after about 700 ka (Figures 1, 2), indicating slow ice buildup and subsequent rapid melting, also reflects nonlinear forcing of the climate system (Maslin and Ridgwell, 2005). Most hypotheses for the origin of the MPT invoke a response to long-term cooling, driven by such possible mechanisms as ice-sheet dynamics (Clark et al., 2006) or a secular decline in atmospheric CO_2 (Maslin and Ridgwell, 2005).

To elucidate variations in cyclicity over the past 1500 kyr, we briefly present the wavelet analysis of a compilation of marine benthic foraminiferal $\delta^{18}O$ records known as the LR04 stack (Lisiecki and Raymo, 2005). We then review major climatic events from the marine and terrestrial realms (from Head and Gibbard, 2005 and references therein, unless otherwise stated; Figure 1); and because the MPT has long been used to broadly define the boundary between the Early and Middle Pleistocene, we finally summarize recent progress in assessing candidate GSSPs for a formal definition of the Early–Middle Pleistocene Sub-series/Sub-epoch boundary.

Wavelet analysis

Wavelet spectra are useful for analyzing localized variations of power within a time series (Torrence and Compo, 1998). The LR04 stack averages $\delta^{18}O$ records from 57 sites, and produces a global signal relatively free of local effects. Wavelet analysis of this stack was performed using the MATLAB® Wavelet Toolbox™ (following Torrence and Compo, 1998) with the following parameters: continuous wavelet 1-D; wavelet = Morlet; scale settings: 'step by step mode'; min = 1; step = 1; max = 64. The cone of influence (as defined by Torrence and Compo, 1998) = 2^(1/2) x scale. Our analysis of this stack (Figure 2) shows that:

1) low frequency variability: i) begins at 1.25–1.20 Ma (Marine Isotope Stage [MIS] 38–36) with increased power in the 70-kyr band; ii) gains power in the 85–110-kyr band from c. 1000–900 ka (MIS 29–23), with power in this band intensifying from c. 700–650 ka (MIS 17–16); and iii) is complex and quasi-periodic within the detection limits of this time span.

2) power in the 41-kyr obliquity-dominated band remains constant through the examined interval, and precession-related cyclicity at c. 23 kyr is also present throughout.

Our results broadly compare with those from other time series analyses, such as the moving window Fourier transform used by Clark et al. (2006) on the LR04 stack. However, wavelet analysis methods provide an improvement on the Fourier techniques, especially where there are transient shifts in the periodicities of the responses to forcing patterns. Thus, although Clark et al. (2006) showed that the c. 100-kyr climate cycle emerged at 1.25 Ma and reached full amplitude by 700 ka, wavelet analysis reveals a more detailed and complex picture of low frequency variability beginning at 1.25–1.20 Ma and evolving through the interval examined, as detailed above.

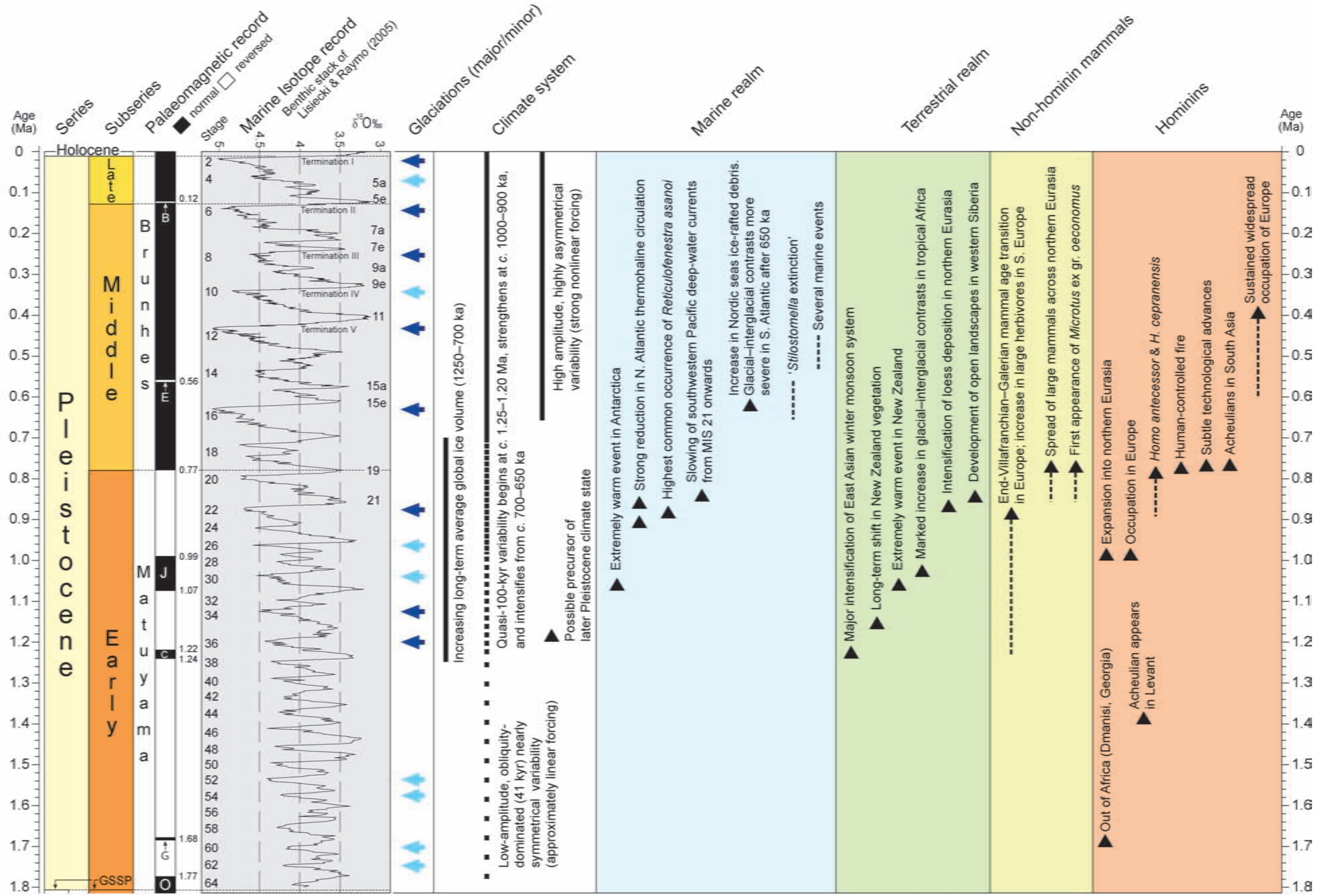

***Figure 1** Major events during the Early–Middle Pleistocene transition adapted from Head and Gibbard (2005, Figure 2) and using the marine benthic foraminiferal $\delta^{18}O$ stack of Lisiecki and Raymo (2005). For the magnetostratigraphy: B = Blake Event, E = Emperor Event, J = Jaramillo Subchron, C = Cobb Mountain Event, G = Gilsa Event, O = Olduvai Subchron (top only).*

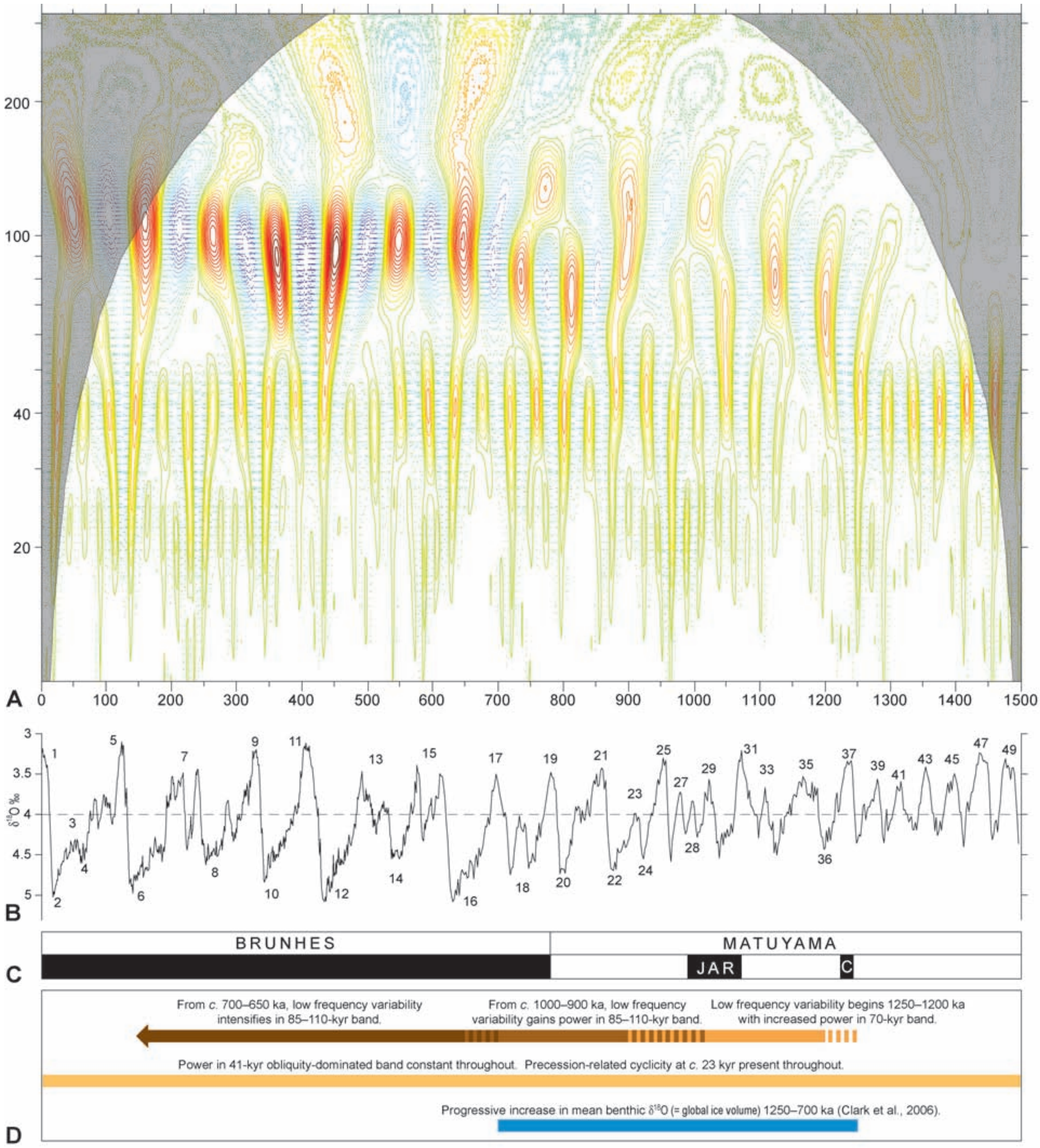

***Figure 2** A. Wavelet spectrum of the LR04 stack for the interval 0–1500 ka (see text for details). B. The corresponding LR04 stack of benthic foraminiferal $\delta^{18}O$ records from 57 globally distributed sites (Lisiecki and Raymo, 2005). C. Magnetostratigraphy showing the position of the Matuyama–Brunhes boundary, which we propose as the primary chronostratigraphic guide for the Early–Middle Pleistocene boundary. JAR = Jaramillo Subchron, C = Cobb Mountain Event. D. Main transitions indicated by the wavelet spectrum of the LR04 stack. The interval of global ice increase (Clark et al., 2006) is also given.*

Marine records

The MPT is characterized by a long-term average global ice-volume increase between 1.25 Ma and 700 ka (Clark et al., 2006). MIS 36 (c. 1.20 Ma) coincides approximately with the beginning of low-frequency oscillations (Figure 2), supporting suggestions that this was a precursor to the later Pleistocene nonlinear state. However, both marine (Clark et al., 2006) and terrestrial records (Sun et al., 2006, see below) imply a slightly earlier age (1.25 Ma) for the onset of severe climatic conditions. In the southeastern South Atlantic, contrasts in glacial–interglacial ocean circulation strengthened from this time onwards. MIS 24 and 22 (920 and 880 ka) represent the first major cooling phase of the MPT and are associated with strong reductions in North Atlantic thermohaline circulation. The MIS 23–22 transition (c. 890 ka) is associated with the highest common occurrence of the nannofossil *Reticulofenestra asanoi*, an important datum for the MPT in the Mediterranean and North Atlantic. Decreased production of North Atlantic Deep Water (NADW) during the MPT was likely the result of increased northern hemisphere glaciation, with increased ice-rafted debris evident in the Nordic seas from about 650 ka. At least 50 species of deep-sea benthic foraminifera are known to have become extinct during the MPT. These data probably reflect slower deep ocean circulation and reduced deep-water ventilation during the MPT. Marine events are depicted on Figure 1.

Continental records

Evidence for climate change is more visible, if less complete, on land. The classic loess–paleosol sequences of northern Eurasia and China are among the longest complete continental records of the Quaternary, revealing the alternation of dry and humid conditions on orbital time scales correlated to the marine record. Several key events are recognized from the Chinese Loess Plateau: the interval 1.25–0.52 Ma represents a substantial increase both in the amplitude of the winter monsoon variation and its intensity, and a weakened summer monsoon (Sun et al., 2006). The deserts in northern China are inferred to have expanded significantly at around 1.2 Ma (Ding et al., 2005). After 0.52 Ma, the mean and amplitude of both the summer and winter monsoon variation increased greatly (Sun et al., 2006). The appearance of thicker loess horizons in northern Eurasia after about 1.0 Ma marks the onset of more pronounced c. 100-kyr cycles, with loess accumulation becoming particularly intensified during the severely cold conditions associated with MIS 22 (Dodonov, 2005). In the Chinese Loess Plateau, both the upper part of the L9 loess horizon (MIS 22, 0.87 Ma) and the loess horizon L15 (MIS 38, 1.25 Ma) have especially high peaks in the coarser sediment fraction (Sun et al., 2006), and reflect severe climatic conditions.

Other continental paleoenvironmental records, particularly from lacustrine and fluvial sediments, reveal complex responses through the MPT. For example, a major shift occurs in the pollen record of a site in New Zealand at MIS 35, resulting in a permanent increase in southern beech forests. Tzedakis et al. (2006) showed using a pollen record from Greece that extreme glacial conditions during MIS 22 and 16 were largely responsible for the extirpation of many relict taxa. However, the extinction of themophilous plant taxa was not restricted to the MPT but time-transgressive over much of the Quaternary, with extinctions occurring earlier in northern (colder) parts than in southern parts of the Mediterranean province. Thus, extinctions of plant taxa are not generally suitable for use as high-resolution chronostratigraphic horizons in the Quaternary.

The large and small mammal records show significant regional reorganizations through the MPT, including the first European records of the extant leopard and spotted hyaena. As open landscapes developed, the steppe mammoth first appeared across northern Eurasia at around 850–770 ka. Hominins underwent a complex history of migrations and evolution during the MPT, including early migrations into higher northern latitudes by about 1.0 Ma, probably following migrations of large herbivores that would have served as a food and commodity source, and critically leading to increased colonizing capacity. Continental events are depicted on Figure 1.

Middle Pleistocene GSSP

Fundamental changes in the Earth's climate system, and associated biotic and physical events, occurred progressively during the interval c. 1.2 to 0.5 Ma. Consequently, several positions for the Early–Middle Pleistocene boundary have been suggested (see Head and Gibbard, 2005 for discussion), including the MIS 22–21 transition and the originally-proposed boundary between the Calabrian and Ionian marine stages in Italy (perhaps within MIS 25, but see below). However, support has been greatest for the Matuyama–Brunhes boundary (see Head and Gibbard, 2005 for discussion). For example, participants at 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 should be so defined as to either coincide with or be linked to the boundary between the Matuyama Reversed Epoch and the Brunhes Normal Epoch of paleomagnetic chronology' (Butzer and Isaac, 1975, appendix 2). A similar recommendation was made by the International Union for Quaternary Research (INQUA) Working Group on Major Subdivision of the Pleistocene at the XIIth INQUA Congress in Ottawa in 1987 (Richmond, 1996). There has since been widespread use of the Matuyama–Brunhes boundary (MBB) in defining the Early–Middle Pleistocene boundary (e.g., Bowen, 1988; Berggren et al., 1995; Gradstein et al., 2005). It should be noted that in newly redefining the Italian marine stages, Cita et al. (2006) and Cita (this issue) have now proposed the Matuyama–Brunhes boundary as the guiding criterion for the base of the Ionian Stage. This would result in a satisfactory unification of the Early–Middle Pleistocene boundary with the Calabrian–Ionian Stage boundary in Italy.

At the XIVth INQUA Congress in Berlin in 1995, the search for a suitable boundary stratotype section was focussed on three sections in Japan, New Zealand, and Italy. However, the New Zealand section was discounted because it contained unconformities.

In 2002, a Working Group of the International Commission on Stratigraphy (ICS) Subcommission for Quaternary Stratigraphy was established to review all aspects of the Early–Middle Pleistocene boundary including its position within the MPT and selection of a suitable GSSP. At the 32nd International Geological Congress in Florence in 2004, the Working Group recommended that:

1. The E–M Pleistocene boundary be defined in a marine section at a point 'close to' the Matuyama–Brunhes boundary. The definition of 'close' was agreed to mean within plus or minus one isotope stage of the MBB.
2. The GSSP should be located in a marine section exposed on land, not in a deep sea core.

Three candidate sections are presently being considered by the Working Group:

1. Montalbano Jonico section in Italy (Ciaranfi and D'Alessandro, 2005).
2. Valle di Manche section in Italy (Capraro et al., 2005).
3. Chiba section in Japan (Pickering et al., 1999).

Of the first two, the Montalbano Jonico section is expanded relative to the Valle di Manche section, but weathering has caused difficulties for developing a magnetostratigraphy at Montalbano Jonico (Cita, this issue).

The chronostratigraphic importance of the Matuyama–Brunhes reversal

Chronostratigraphic markers should ideally be recognized in both marine and continental sequences. Widespread tephra beds are regionally useful, as are Australasian tektites (Pillans, 2003), but the MBB offers truly global potential. It also occurs at around the middle of the MPT as defined by the events summarized above, within the interval of increasing global ice volume, and within the transitional interval (c. 1000–900 to 700–650 ka) identified in our own wavelet analysis of the LR04 stack (Figure 2). Moreover, it is close in age to a major glacial event represented by MIS 22 (Figure 1).

High-resolution marine studies give a duration of 5–7 ka and a mid-point at about 773 ka for the MBB (Channell et al., 2004). The MBB coincides with the middle of MIS 19, although problems of displaced magnetic remanence in northern Eurasian and Chinese loess–palaeosol sequences cause it to occur misleadingly in sediments assigned to MIS 20 (Zhou and Shackleton, 1999; Dodonov, 2005). Nonetheless, the MBB remains a crucial stratigraphic guide both on land and at sea.

In closing, we concur with Butzer and Isaac (1975), Richmond (1996), Pillans (2003), and Head and Gibbard (2005) that the MBB should be the primary chronostratigraphic guide for defining and correlating the Early–Middle Pleistocene boundary. However, we emphasize that the MBB is only one of multiple criteria that will be used for local, global and regional correlation of the boundary.

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References

Berggren, W.A., Hilgen, F.J., Langereis, C.G., Kent, D.V., Obradovich, J.D., Raffi, I., Raymo, M.E. and Shackleton, N.J., 1995. Late Neogene chronology: New perspectives in high-resolution stratigraphy: Geological Society of America Bulletin, 107, pp. 1272–1287.

Bowen, D.Q., 1988. Quaternary Geology: A Stratigraphic Framework for Multidisciplinary Work: Pergamon Press, Oxford, 237 pp.

Butzer, K.W., and Isaac, G.L. (Editors), 1975. After the Australopithecines. Mouton, The Hague, 911 pp.

Capraro, L., Asioli, A., Backman, J., Bertoldi, R., Channell, J.E.T., Massari, F., and Rio, D., 2005. Climatic patterns revealed by pollen and oxygen isotope records across the Matuyama–Brunhes Boundary in the central Mediterranean (southern Italy). *In*: M.J. Head and P.L. Gibbard (Editors), Early–Middle Pleistocene transitions: the land–ocean evidence: Geological Society of London, Special Publication 247, pp. 159–182.

Channell, J.E.T., Curtis, J.H., and Flower, B.P., 2004. The Matuyama–Brunhes boundary interval (500–900 ka) in North Atlantic drift sediments: Geophysical Journal International, 158, pp. 489–505.

Ciaranfi, N., and D'Alessandro, A., 2005. Overview of the Montalbano Jonico area and section: a proposal for a boundary stratotype for the lower–middle Pleistocene, Southern Italy Foredeep: Quaternary International, 131, pp. 5–10.

Cita, M.B., Capraro, L., Ciaranfi, N., Di Stefano, E., Marino, M., Rio, D., Sprovieri, R., and Vai, G.B., 2006. Calabrian and Ionian: A proposal for the definition of Mediterranean stages for the Lower and Middle Pleistocene: Episodes, 29, pp. 107–114.

Clark, P.U., Archer, D., Pollard, D., Blum, J.D., Riale, J.A., Brovkin, V., Mix, A.C., Pisias, N.G., and Roy, M., 2006. The middle Pleistocene transition: characteristics, mechanisms, and implications for long-term changes in atmospheric pCO_2: Quaternary Science Reviews, 25, pp. 3150–3184.

Ding, Z.L., Derbyshire, E., Yang, S.L., Sun, J.M., and Liu, T.S., 2005. Stepwise expansion of desert environment across northern China in the past 3.5 Ma and implications for monsoon evolution: Earth and Planetary Science Letters, 237, pp. 45–55.

Dodonov, A.E., 2005. The stratigraphic transition and suggested boundary between the Early and Middle Pleistocene in the loess record of northern Eurasia. *In*: M.J. Head and P.L. Gibbard (Editors), Early–Middle Pleistocene transitions: the land–ocean evidence: Geological Society of London, Special Publication 247, pp. 209–219.

Gradstein, F.M., Ogg, J.G., and Smith, A.G., 2005. A geologic time scale 2004: Cambridge University Press, Cambridge, 589 pp. [Imprinted 2004].

Head, M.J., and Gibbard, P.L., 2005. Early–Middle Pleistocene transitions: an overview and recommendation for the defining boundary. *In:* M.J. Head and P.L. Gibbard (Editors), Early–Middle Pleistocene transitions: the land–ocean evidence: Geological Society of London, Special Publication 247, pp. 1–18.

Lisiecki, L.E., and Raymo, M.E., 2005. A Pliocene–Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records: Paleoceanography, 20, PA1003, doi:10.1029/2004PA001071.

Maslin, M.A., and Ridgwell, A.J., 2005. Mid-Pleistocene revolution and the 'eccentricity myth'. *In*: M.J. Head and P.L. Gibbard (Editors), Early–Middle Pleistocene transitions: the land–ocean evidence: Geological Society of London, Special Publication 247, pp. 19–34.

Pickering, K.T., Souter, C., Oba, T., Taira, A., Schaff, M., and Platzman, E., 1999. Glacio-eustatic control on deep-marine clastic forearc sedimentation, Pliocene–mid Pleistocene (c. 1180–600 ka) Kazusa Group, Japan: Journal of the Geological Society, London, 156, pp. 125–136.

Pillans, B., 2003. Subdividing the Pleistocene using the Matuyama–Brunhes boundary (MBB): an Australasian perspective: Quaternary Science Reviews, 22, pp. 1569–1577.

Richmond, G.M., 1996. The INQUA-approved provisional Lower–Middle Pleistocene boundary. *In*: C. Turner (Editor), The early Middle Pleistocene in Europe. Balkema, Rotterdam, pp. 319–327.

Sun, Y., Clemens, S.C., An, Z., and Yu, Z., 2006. Astronomical timescale and paleoclimatic implications of stacked 3.6-Myr monsoon records from the Chinese Loess Plateau: Quaternary Science Reviews, 25, pp. 33–48.

Torrence, C., and Compo, G.P., 1998. A practical guide to wavelet analysis: Bulletin of the American Meteorological Society, 79, pp. 61–78.

Tzedakis, P.C., Hooghiemstra, H., and Pälike, H., 2006. The last 1.35 million years at Tenaghi Philippon: revised chronostratigraphy and long-term vegetation trends: Quaternary Science Reviews, 25, pp. 3416–3430.

Zhou, L.P., and Shackleton, N.J., 1999. Misleading positions of geomagnetic reversal boundaries in Eurasian loess and implications for correlation between continental and marine sedimentary sequences: Earth and Planetary Science Letters, 168, pp. 117–130.

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by Thomas Litt[1] and Philip Gibbard[2]

Definition of a Global Stratotype Section and Point (GSSP) for the base of the Upper (Late) Pleistocene Subseries (Quaternary System/Period)

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Following the precedence already established during the INQUA Congress in 1932, the Middle/Upper (Late) Pleistocene boundary is defined at the base of the Last Interglacial, the Eemian Stage. It is proposed that a high-resolution core sequence from the Amsterdam Terminal (the Eemian Stage parastratotype) should constitute the Global Stratotype Section and Point (GSSP) for the base of the Upper (Late) Pleistocene Subseries (Quaternary System/Period). The core contains a proxy climate record across the Middle/Upper (Late) Pleistocene boundary as indicated by different biotic and abiotic parameters reflecting the first signs of climate warming at the end of the Saalian cold Stage. For the beginning of the Eemian Stage in Europe, the date of 127.2 ka from the varved-dated record of Monticchio in Italy can be taken as the best estimate of age.

Boundary stratotype—state of the art

The basic principles used in subdividing the Pleistocene as a Series into chronostratigraphical units are the same as for other Phanerozoic units which require boundary definitions and the designation of boundary stratotypes (Salvador, 1994). However, in contrast to the rest of the Phanerozoic, the division of Quaternary sequences on the basis of climatic changes documented in the sedimentary record is fundamental and has a long tradition. Classifications based on climatostratigraphical units are reasonably well-established in different countries, or areas and are accepted as regional chronostratigraphical standards (Gibbard and West, 2000, Gibbard and van Kolfschoten, 2004)

In terms of the subdivision of the Pleistocene, a quasi-formal tripartite classification into Lower (Early), Middle and Upper (Late) Pleistocene as a subseries is generally used. The boundary between the Middle and Upper Pleistocene has not yet been formally defined by IUGS. However, already during the 2nd INQUA Congress in Leningrad in 1932 the decision was made to define the Middle/Upper (Late) Pleistocene boundary at the base of the Last Interglacial, the Eemian Stage (Woldstedt, 1962). Both the Last Interglacial and the Last Glacial (Weichselian, Würmian, Wisconsinan, Valdaian and equivalents) are considered to be included into the Upper (Late) Pleistocene (Figure 1). More recently the lower boundary of the Upper (Late) Pleistocene has been placed at the base of Marine Isotope Stage 5 (MIS 5) by Richmond (1996) based on a proposal of the INQUA Subcommission on Stratigrahy (unpublished). This proposal followed the view that the MIS 5e Substage in the ocean sediments is equivalent to the northwest European Eemian Interglacial Stage on land (Shackleton, 1977). Although it may seem attractive to define the boundary in an ocean-sediment sequence, the inherent imprecision of most of such sequences, resulting from slow sedimentation rate, combined with the effects of bioturbation, suggests that for high-resolution stratigraphical purposes they are generally unsuitable for the definition of 'golden spike'-type, 'time-plane' boundaries. In addition, the direct comparison between terrestrial pollen, benthic/planktonic foraminifera and isotopes from the same deep-sea core west of Portugal shows that temperature changes are not in phase with ice volume variations (Figures 1 and 3). Pronounced offsets between marine isotopic warm stages boundaries and forested intervals were described by Sánchez Goñi et al. (1999) for MIS 5 (see below). To obviate this problem, following the precedence established 75 year ago, Gibbard (2003) proposed that the Middle/Upper Pleistocene boundary stratotype (the Global Stratotype Section and Point—GSSP) should be defined in the newly-processed high-resolution core sequence from the Amsterdam-Terminal (the Eemian Stage parastratotype, cf. van Leeuwen et al. 2000, see Figure 2). This proposal is currently under examination by a working group of the International Subcommission on Quaternary Stratigraphy.

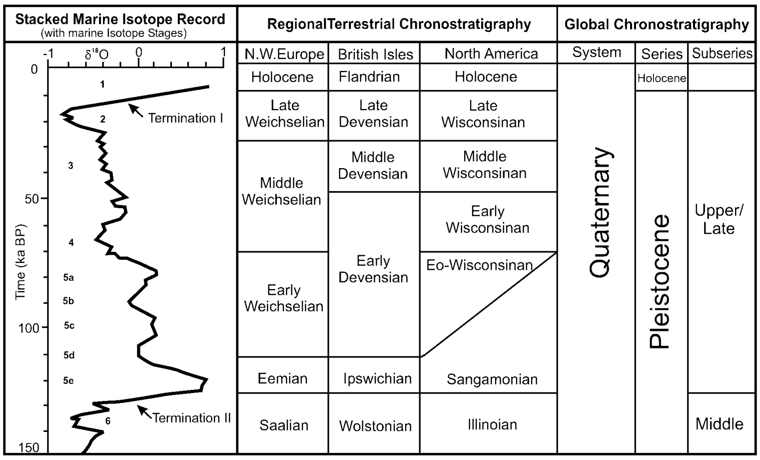

***Figure 1** Marine and continental chronostratigrahy for the past 150 kyr. The stacked marine oxygen isotope sequence and associated stages are from Martinson et al. (1987). (Modified after Gibbard and van Kolfschoten, 2004.) Note that the MIS 6/5e boundary (Termination II) have been significantly earlier than the Saalian/Eemian stage boundary on land (see also Figure 3). A similar pronounced offset between marine isotopic warm stage boundary 2/1 (Termination I) and the Plesitocene/Holocene boundary occurs.*

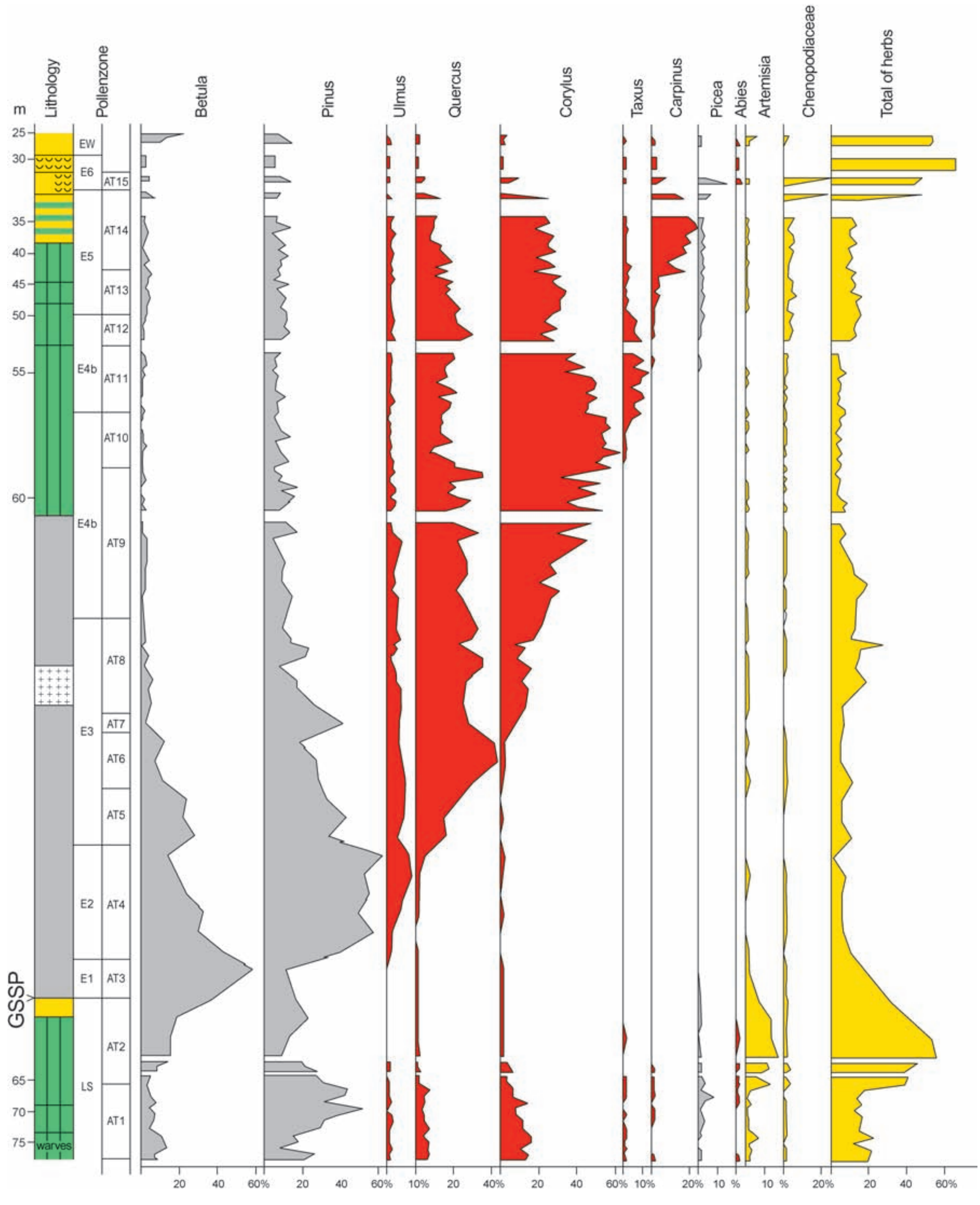

Figure 2 Amsterdam-Terminal borehole (the Netherlands) and pollen assemblages. The proposed stratotype boundary horizon is based on the steep rise of the Betula pollen curve at this point (after van Leeuwen et al. 2000).

Correlation on land

The proposed stratotype boundary horizon in the Amsterdam Terminal borehole is based on the steep rise of the *Betula* pollen curve at this point (Figure 2). A similar rise in the *Betula* curve can be seen in Eemian Interglacial pollen diagrams from England, across the North European plain to Poland and Russia in shallow marine, as well as terrestrial sediment sequences (Menke and Tynni 1984, Turner 2002). Representative sites that show this horizon include Gröbern in central Germany (Litt et al., 1996), Imbramowice in Poland (Mamakowa 1989) and Cheremoshnik in the Rostov Veliky region of Russia (Velichko et al. 2005).

The argument for regarding this horizon at which *Betula* expanded as being more or less synchronous, within the limits of precision for defining a stratotype during this time interval, are twofold. Firstly, the expansion of the *Betula* pollen curve is seen as a vegetational response to climatic amelioration, with tree-birches beginning to form woodland communities in response to increased solar radition and the renewed influence of the warm waters of the revived North Atlantic currents that affected not just the western coastlands of Europe but the whole climate of northern Eurasia even beyond the Ural mountains to Central Asia. The second relies on comparisons with events at the end of the last glacial stage (Weichselian, Würmian, Valdaian, Wisconsinan). Evidence relating to the Late Weichselian Younger Dryas Stadial-Holocene transition sug-

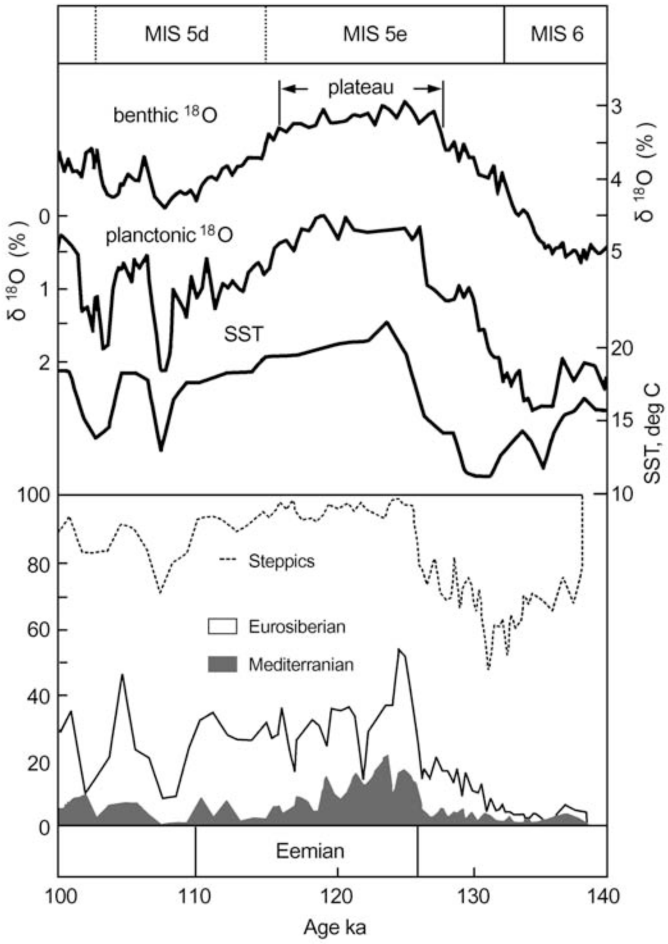

Figure 3 Marine and continental records of the last interglacial in core MD95-2042 (west of Portugal). The MIS 6/5e boundary differs significantly to those of the Saalian/Eemian stage boundary on land identified by pollen analysis of the marine sedi-ments (after Shackleton et al., 2002).

gests that the expansion of tree-birches was almost synchronous at that time (even perhaps within a matter of decades) across this whole region (Litt et al., 2001, 2003). The same arguments are used in attempting correlation with pollen sequences from southern Europe, where evidence is available both from Atlantic marginal cores west of Portugal (Sanchez-Goñi et al., 1999) and from a number of deep lake basins in the Mediterranean region (Brauer et al., 2007, Follieri et al., 1988; Tzedakis, 1994; Wijmstra and Smit, 1976). Sites in the French Massif Central (Reille et al., 1998; de Beaulieu and Reille, 1992) provide an intermediate situation between northern Europe and the Mediterranean. At these sites the horizon corresponding to the stratotype boundary horizon in the Netherlands is seen as being marked by a major expansion of forest trees, in particular by the rise of the pollen curve of *Quercus*, but perhaps most markedly the abrupt collapse of the pollen curves of steppic taxa such as *Artemisia* and Chenopodiaceae. Here again the interpreted vegetational changes are so intense and abrupt that they must be a response to a powerful climatic signal, assumed to be the same combination of increasing solar radiation and Atlantic circulation changes that relate to the vegetation changes used to define the stratotype horizon in the Netherlands.

Because the onset of the Last Interglacial forest expansion in southern and northern Europe appears to be relative synchronous (Tzedakis, 2003), for the beginning of the Eemian in the entire Europe the date of 127,2 ka from the varved-dated record of Monticchio (Brauer et al., 2007) can be chosen as a direct geochronological tie-point based on a calendar-year time scale.

Land-sea correlation

Of particular importance for Pleistocene stratigraphy are the essentially time-parallel periods of rapid climate change termed 'terminations' (Broecker and van Donk, 1970), seen in ocean sediment oxygen isotope sequences. The major, dramatic changes in world ice-volume so indicated, imply climate shift from full-glacial to interglacial conditions over short timespans of a few millenia that may appear as 'abrupt' events at commonly-used graphic scales. In favourable situations, these sharp changes can also be recognized on land as dramatic changes in pollen assemblage composition or other parameters; for example where sufficiently long and detailed sequences are available, such as in long lake cores (cf. Tzedakis et al., 1997). It may then, on face-value, seem attractive to attempt to use such termination events as a potential means for land-sea correlation. However, their value for correlation may be limited in high sedimentation-rate sequences because the 'terminations' are not instantaneous, but represent several thousand years (Broecker and Henderson, 1998). These matters clearly concern questions of resolution and scale.

Termination II marks the major shift immediately before MIS 5, the change thought to represent the climatic event represented by the Saalian-Eemian (and equivalents) stage boundary in NW Europe. Martinson et al. (1987) calculated the date of the base of MIS 5 at c.130 ky B.P., i.e., corresponding to the end of Termination II of the marine oxygen isotope sequences (Broecker and Van Donk, 1970). More recently the mid-point of Termination II was recalculated to 128 ky; the amelioration beginning at 132 ky and ending 6 ky years later at 126 ky, based on data from a series of high-resolution ocean core profiles (Broecker and Henderson, 1998). On this basis the Last Interglacial duration would be 129–119 ky, based on use of mid-points for defining MI stage or substage boundaries, according to Broecker and Henderson (1998).

The precise recognition and timing of boundaries or events from the ocean sediment (MI) stages on land and *vice versa* is of great concern for the development of a fully-integrated, high-resolution terrestrial–marine global stratigraphy. However, the differing rates and ways that different proxies respond to climate changes and these changes themselves may be multifactoral and time-transgressive. That boundaries defined using different proxies do not necessarily invariably occur at the same time has been graphically demonstrated by the work west of Portugal by Sanchez-Goñi et al. (1999) and Shackleton et al. (2002). Here the MIS 6/5e boundary has been shown to have been significantly earlier than the Saalian / Eemian stage boundary on land identified by pollen analysis of the marine sediments (Figure 3). The Eemian interglacial (sensu stricto) must coincide only with the lightest isotopic values of Substage 5e beginning at 126 ky. Thus if high-resolution terrestrial sequences and low-resolution marine sequences are to be correlated accurately, one clearly cannot assume that the boundaries recognized in these very different environmental situations are indeed coeval (cf. Gibbard and West, 2000, Gibbard, 2002).

A similar problem arises for the Italian marine stage nomenclature in which the term Tarantian was proposed over ten years ago (Cita and Castradori, 1994;1995; van Couvering, 1995) for the interval from the MIS 6/5 boundary or Termination II to the base of the Holocene (Cita this volume). For reasons of internal consistency and heirarchy, the basal boundary of both this stage and that of the Upper (Late) Pleistocene Subseries must coincide.

References

Brauer, A., Allen, J.R.M., Mingram, J., Dulski, P., Wulf, S., and Huntley, B., 2007, Evidence for last interglacial chronology and environmental change from Southern Europe: PNAS, v. 104, pp, 450–455.

Broecker, W.S., and Henderson, G.M., 1998, The sequence of events surrounding Termination II and their implications for the cause of glacial-interglacial CO2 changes: Paleooceanography, v. 13, pp. 352–364.

Broecker, W.S., and Van Donk, J., 1970, Insolation changes, ice volumes and the 18O record in deep-sea cores: Review of Geophysics and Space Physics, v. 8, pp. 169–198.
Colhoun, E.A., Pola, J.S., Barton, C.E., and Heijnis, H., 1999, Late Pleistocene vegetation and climate history of Lake Selina, western Tasmania: Quaternary International, v. 57/58, pp. 5–23.
Cita, M.B., 2008, Summary of Italian marine stages: Episodes, this volume.
Cita, M.B., and Castradori, D., 1994, Workshop on marine sections of Gulf of Taranto (Southern Italy) usable as potential stratotypes for the GSSP of the Lower, Middle and Upper Pleistocene: Il Quaternario, v. 7, pp. 677–692.
Cita, M.B., and Castradori, D., 1995, Rapporto sul Workshop "Marine sections from the Gulf of Taranto (Southern Italy) usable as potential stratotypes for GSSP of the Lower, Middle and Upper Pleistocene": Bollettino della Società Geologica Italiana, v.114, pp. 319–336.
De Beaulieu J.-L., and Reille, M., 1992, Long Pleistocene pollen sequences from the Velay Plateau (Massif Central, France). I. Ribains maar : Vegetation History and Archaeobotany, v. 1, pp. 233–242.
Follieri, M., Magri, D., and Sadori, L., 1988, 250,000-year pollen record from Valle di Castiglione (Roma): Pollen et Spores, v. 30, pp. 329–356.
Gibbard, P.L., 2003, Definition of the Middle-Upper Pleistocene boundary: Global and Planetary Change, v. 36, pp. 201–208.
Gibbard. P. L., and van Kolfschoten, T., 2004, The Pleistocene and Holocene Epochs, in Gradstein, F., Ogg, J., and Smith, A., eds, A Geologic Time Scale 2004: Cambridge, Cambridge University Press, pp. 441–452.
Gibbard, P.L., and West, R.G., 2000, Quaternary chronostratigraphy: the nomenclature of terrestrial sequences, Boreas, v. 29, pp. 329–336.
Litt, T., Brauer, A., Goslar, T., Merkt, J., Balaga, K., Müller, H., Ralska-Jasiewiczowa, M., Stebich, M., and Negendank, J.F.W., 2001, Correlation and synchronisation of Lateglacial continental sequences in northern central Europe based on annually laminated lacustrine sediments: Quaternary Science Reviews, v. 20, pp. 1233–1249.
Litt, T., Junge, F.W., Böttger, T., 1996, Climate during the Eemian in north-central Europe – a critical review of the palaeobotanical and stable isotope data from central Germany: Vegetation History and Archaeobotany, v. 5, pp. 247–256.
Litt, T., Schmincke, H.-U., and Kromer, B., 2003, Environmental response to climate and volcanic events in central Europe during the Weichselian Lateglacial: Quaternary Science Reviews, v. 22, pp. 7–32.
Mamakowa, K., 1989, Late Middle Polish glaciation, Eemian and Early Vistulian vegetation at Imbramowice near Wroclaw and the pollen stratigraphy of this part of the Pleistocene in Poland: Acta Palaeobotanica, v. 29, pp. 11–176.
Menke, B., and Tynni, R., 1984, Das Eeminterglazial und das Weichselfrühglazial von Rederstall/Dithmarschen und ihre Bedeutung für die mitteleuropäische Jungpleistozän-Gliederung: Geologisches Jahrbuch, v. A 76, pp. 3–120.
Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C., and Shackleton, N.J., 1987, Age dating and the orbital theory of the ice ages: development of a high-resolution0 to 300 000 year chronostratigraphy: Quaternary Research, v. 27, pp. 1–29.
Reille, M., Andrieu, V., de Beaulieu, J-L., Guenet, P., and Goeury, C., 1998, A long pollen record from Lac du Bouchet, Massif Central, France: for the period ca. 325 to 100 ka (OIS 9c to OIS 5e): Quaternary Science Reviews, v. 17, pp. 1107–1123.
Richmond, G.M., 1996, The INQUA-approved provisional Lower-Middle Pleistocene boundary, in Turner, C. ed, The early Middle Pleistocene in Europe: Rotterdam, Balkema, pp. 319–326.
Salvador, A., ed, 1994, International Stratigraphic Guide: A guide to stratigraphic classification, terminology, and procedure. 2nd edition, International Union of Geological Science / Geological Society of America, Trondheim, Boulder, 214 pp.
Sanchez-Goñi M.F., Eynaud, F., Turon, J.L. and Shackleton, N.J., 1999. High resolution palynological correlation off the Iberian margin: direct land-sea correlation for the Last interglacial complex: Earth and Planetary Science Letters, v. 171, pp. 123–137.
Shackleton, N.J., 1977, The oxygen isotope stratigraphic record of the Late Pleistocene: Philosophical Transactions of the Royal Society of London, . B 280, p. 169–182.
Shackleton, N.J., Chapman, M., Sanchez-Goñi, M.F., Pailler, D., and Lancelot, Y., 2002, The classic Marine Isotope Substage 5e: Quaternary Research, v. 58, pp. 14–16.
Turner, C., 2002, Formal Status and Vegetational Development of the Eemian Interglacial in Northwestern and Southern Europe: Quaternary Research, v. 58, pp. 41–44.
Tzedakis, P.C., 1994, Vegetation change through glacial-interglacial cycles: a long pollen sequence perspective: Philosophical Transactions of the Royal Society of London, v. B 345, pp. 403–432.
Tzedakis, P.C., 2003, Timing and duration of Last Interglacial conditions in Europe: a chronicle of a changing chronology: Quaternary Science Reviews, v. 22, pp. 763–768.
Tzedakis, P.C., Andrieu, V., Beaulieu, J.L. de, Crowhurst, S., Follieri, M., Hooghiemstra, H., Magri, D., Reille, M., Sadori, L., Shackleton, N.J. and Wijmstra, T.A., 1997, Comparison of terrestrial and marine records of changing climate of the last 500 000 years: Earth and Planetary Science Letters, v. 150, pp. 171–176.
Van Couvering, J.A., 1995, Setting Pleistocene Marine Stages: Geotimes, v. 40, pp. 10–11.
Van Leeuwen, R.J.W., Beets, D.J., Bosch, J.H.A., Burger, A.W., Cleveringa, P., van Harten, D., Herngreen, G.F.W., Kruk, R.W., Langereis, C.G., M., T., Pouwer, R., and de Wolf, H., 2000, Stratigraphy and integrated facies analysis of the Saalian and Eemian sediments in the Amsterdam-Terminal borehole, the Netherlands: Geologie en Mijnbouw, v. 79, pp. 161–196.
Velichko, A.A., Novenko, E.Y., Pisareva, V.V., Zelikson, E.M. Boettger, T., and Junge, F.W. 2005, Vegetation and climate changes during the Eemian interglacial in Central and Eastern Europe: comparative analysis of pollen data: Boreas, v. 34, pp. 207–219.
Wijmstra, T.A., and Smit, A., 1976, Palynology of middle part (30–78 meters) of 120 deep section in northern Greece (Macedonia): Acta Botanica Neerlandica, v. 25, pp. 297–312.
Woldstedt, P., 1962, Über die Benennung einiger Unterabteilungen des Pleistozäns: Eiszeitalter und Gegenwart, v. 3, pp. 14–18.

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The Global Stratotype Section and Point (GSSP) for the base of the Holocene Series/Epoch (Quaternary System/Period) in the NGRIP ice core

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The Greenland ice core from NorthGRIP (NGRIP) contains a proxy climate record across the Pleistocene–Holocene boundary of unprecedented clarity and resolution. Analysis of an array of physical and chemical parameters within the ice enables the base of the Holocene, as reflected in the first signs of climatic warming at the end of the Younger Dryas/Greenland Stadial 1 cold phase, to be located with a high degree of precision. This climatic event is most clearly reflected in an abrupt shift in deuterium excess values, accompanied by more gradual changes in $\delta^{18}O$, dust concentration, a range of chemical species, and annual layer thickness. A timescale based on multi-parameter annual layer counting provides an age of 11,700 yr b2k (before AD2000) for the base of the Holocene, with an estimated 2σ uncertainty of 99 yr. It is proposed that an archived core from this unique sequence should constitute the Global Stratotype Section and Point (GSSP) for the base of the Holocene Series/Epoch (Quaternary System/Period)

Introduction

Holocene is the name given to the second series or epoch of the Quaternary System/Period, the most recent interval of Earth history, which extends to and *includes the present day*. Despite being the most intensively studied interval of recent geological time, a definition of the base of the Holocene (the Pleistocene–Holocene boundary) has not been formally ratified by the International Commission on Stratigraphy (ICS). Here we summarise a proposal to the ICS for a Global Stratotype Section and Point (GSSP) for the base of the Holocene Series/Epoch.

The Pleistocene–Holocene boundary

The conventional approach to subdivision of the Quaternary stratigraphic record is to employ evidence for contrasting climate conditions to characterise individual stratigraphic (geologic-climatic) units (American Commission on Stratigraphic Nomenclature, 1961, 1970). For a variety of reasons, however, the Pleistocene–Holocene boundary has proved difficult to define in conventional Quaternary depositional sequences (Morrison, 1969; Bowen, 1978). Moreover, although an age of 10,000 ^{14}C yr BP for the base of the Holocene is widely cited in the Quaternary literature (e.g., Mangerud et al., 1974), precise dating of the boundary has also proved to be problematical (Lowe & Walker, 2000). One context where many of these difficulties may be overcome is the polar archive, and here we present a proposal for defining a GSSP for the Pleistocene–Holocene boundary on the basis of its clear climatic signature in the NorthGRIP (NGRIP) Greenland ice-core record.

The appropriateness of defining a global geological stratotype in an ice-core sequence might be questioned, but there are sound reasons for this proposal:

i) As glacier ice is a sediment, defining the Holocene boundary stratotype in an ice-core is as justified as basing a stratotype on hard or soft rock sequences.

(ii) Ice sheets form through the annual incremental accumulation of snow, and hence there is a continuity of accumulation (sedimentation) across the Pleistocene–Holocene boundary.

(iii) Because of its geographical location in the high latitude North Atlantic, Greenland is a sensitive barometer of hemispherical-scale climate change, and was especially so at the Pleistocene–Holocene transition when the Greenland ice sheet lay mid-way between the wasting Eurasian and Laurentide ice masses.

(iv) The base of the Holocene in the Greenland ice-core record can be very precisely dated by annual ice-layer counting (see below). The boundary stratotype for the Holocene (GSSP) can therefore be defined at a level of chronological precision that is likely to be unattainable in any other terrestrial stratigraphic context.

(v) The Greenland ice-core record has been proposed by an INQUA project group (INTIMATE) as the stratotype for the Late Pleistocene in the North Atlantic region (Walker et al., 1999) and an 'event stratigraphy' was initially developed for the Last Termination based on the oxygen isotope record in the GRIP ice core (Björck et al., 1998). More recently, the INTIMATE group has proposed that the new NGRIP isotopic record should replace GRIP as the stratotype, using the GICC05 chronology described below (Lowe et al., 2008).

The NGRIP ice core

In Greenland, five major deep-drilling programmes (Figure 1) have been undertaken over the last 40 years (Johnsen et al., 2001), the most recent of which, NorthGRIP (NGRIP) was drilled to bedrock in 2003 (borehole NGRIP2, central Greenland ice sheet; 75.10°N; 42.32°W). This is the deepest core so far recovered from Greenland (3085 m), and the base is dated to c. 123 k yr BP (Dahl-Jensen et al., 2002; North Greenland Ice Core Project Members, 2004). The NGRIP cores are archived at the University of Copenhagen, and access to these can be gained through the NGRIP curator via the NGRIP Steering Committee. The NGRIP core contains the most highly-resolved stratigraphic record in any of the Greenland ice cores of the transition from the Pleistocene to the Holocene, and this is reflected in both the visual stratigraphy (annual ice layer thickness) and in a range of chemical indicators (Figure 2). In addition, a high-resolution stratigraphic timescale (Greenland Ice Core Chronology 2005, or GICC05: Vinther et al., 2006; Rasmussen et al., 2006; Andersen et al., 2006) has been developed based on annual layer counting using stable isotopes and high-resolution impurity measurements. It is proposed that the Global Stratotype Section and Point (GSSP) for the base of the Holocene (Pleistocene–Holocene boundary) should be defined in the NGRIP ice-core record at the horizon which marks the clearest signal of climatic change at the end of the last glacial episode (Younger Dryas Stadial/Greenland Stadial 1) of the Pleistocene.

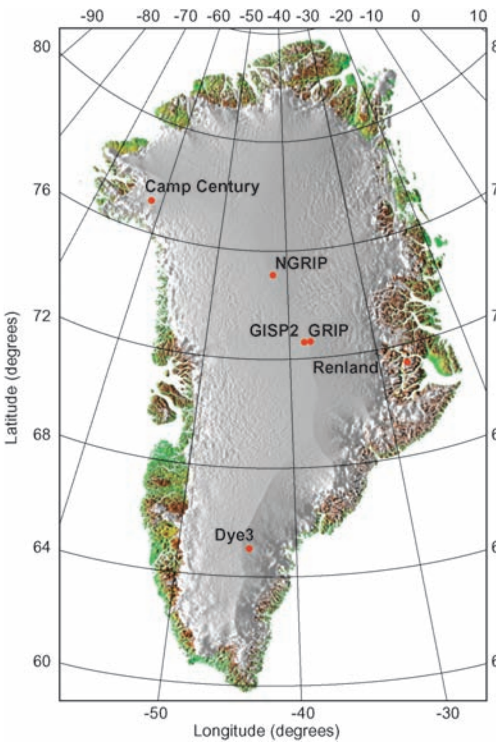

Figure 1 The locations of five deep drilling sites on the Greenland ice sheet: NGRIP (75.1°N, 42.3°W), GRIP (72.5°N, 37.3°W), GISP-2 (72.5°N, 38.3°W), Dye-3 (65.2°N, 43.8°W) and Camp Century (77.2°N, 61.1°W). Also shown is the shallower site (324m) of Renland (71.3°N, 26.7°W). At all of these sites, the ice-core record extends back to the last (Eemian) interglacial. Map by S. Ekholm, Danish Cadastre.

Proposed GSSP for the base of the Holocene Series/Epoch

In the Greenland ice cores, the transition to the Holocene is marked by a shift to 'heavier' oxygen isotope values ($\delta^{18}O$) between Greenland Stadial 1 (GS-1)/Younger Dryas ice and ice of early Holocene age; a rapid decline in dust concentration from GS-1 to modern levels; a significant change in ice chemistry (e.g., reduction in sodium concentration); and an increase in annual ice-layer thickness (Johnsen et al., 2001; Figure 2). These changes reflect a marked change in atmospheric circulation regime accompanied by a temperature rise, of c. 10 ± 4°C, at the onset of the Holocene (Severinghaus et al., 1998; Grachev and Severinghaus, 2005).

In the NGRIP core, this climatic shift is most clearly marked by a change in *deuterium excess* values (Figure 2b: red curve) which occurs before or during the interval over which the changes outlined above are recorded. Deuterium (D) and ^{18}O are important isotopic components of precipitation and in high northern latitudes and the relative deviation per mille (‰) from that in Standard Mean Ocean Water (SMOW) is indicated by δD and $\delta^{18}O$, respectively (Johnsen et al., 1989). The approximate current relationship between δD and $\delta^{18}O$ is given by: $\delta D = 8.0\ \delta^{18}O + 10‰$, the 10‰ being the so-called deuterium excess. Deuterium excess in the Greenland ice-core records indicates changes in the physical conditions at the oceanic origins of arctic precipitation and, in particular, can be considered a proxy for past sea-surface temperature in the moisture source regions of the oceans (Johnsen et al., 1989; Masson-Delmotte et al., 2005; Jouzel et al., 2007). The deuterium excess record shows a 2–3‰ decrease at the Pleistocene–Holocene transition, corresponding to an ocean-surface temperature decline of 2–4°C. This is interpreted as a change in the source of Greenland precipitation from the warmer mid-Atlantic during glacial times to colder higher latitudes in the early Holocene (Johnsen et al., 1989; Masson-Delmotte, et al., 2005). The change reflects a sudden reorganisation of the Northern Hemisphere atmospheric circulation related to the rapid northward movement of the oceanic polar front at the end of the Younger Dryas Stadial/Greenland Stadial 1 (Ruddiman and Glover, 1975; Ruddiman and McIntyre, 1981). Hence the deuterium excess record is an excellent indicator of the first major climatic shift at the Pleistocene–Holocene boundary.

Sampling at 5 cm intervals (annual resolution or greater) across the Pleistocene-Holocene transition in the NGRIP core enables the abrupt decline in deuterium excess to be pinpointed with great precision (Figure 2b). At 1492.45 m depth, the 2–3‰ decrease in deuterium excess occurs within a period of 1–3 yr and, over the next few decades, the $\delta^{18}O$ changes from glacial to interglacial values (reflecting the temperature-dependent nature of the fractionation of oxygen isotopes), and there is an order of magnitude drop in dust concentration, reflecting a reduction in dust flux to the ice sheet. The

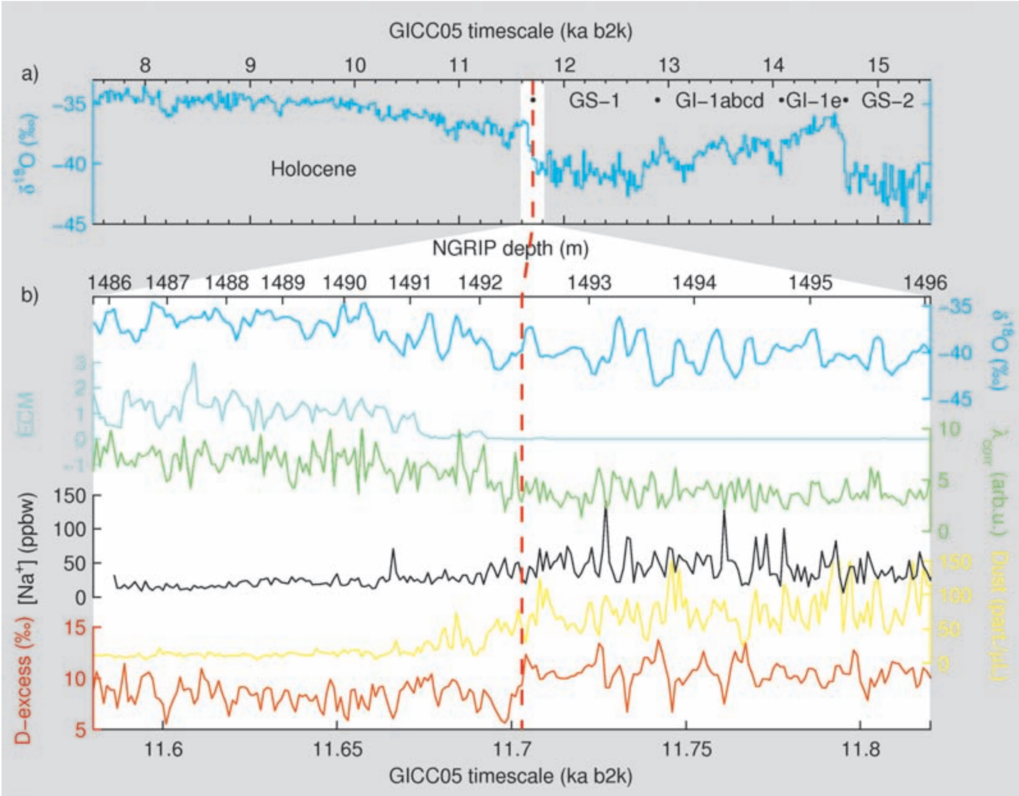

Figure 2 (a) The $\delta^{18}O$ record through the Last Glacial–Interglacial Transition showing the position of the Pleistocene–Holocene boundary in the NGRIP core; (b) High-resolution multi-parameter record across the Pleistocene–Holocene boundary: $\delta^{18}O$, electrical conductivity (ECM), annual layer thicknesses corrected for flow-induced thinning, (^{a}corr) in arbitrary units, Na^{+} concentration, dust content, and deuterium excess.

base of the Holocene can therefore be defined on the basis of the marked change in deuterium excess values that occurred over an interval of c. 3 yr, and the stratigraphic boundary is further underpinned by shifts in several other key proxies that occurred over subsequent decades. As such, the NGRIP ice core constitutes a stratotype for the base of the Holocene of unparalleled detail and chronological precision.

The age of the base of the Holocene is derived from annual ice-layer counting across the Pleistocene–Holocene boundary and through ice from the entire Holocene. This involves the analysis of a range of physical and chemical parameters including dust concentration, conductivity of ice and melted samples, $\delta^{18}O$ and δD, and a range of chemical species including Ca^{2+}, NH^{+}, NO^{-}, Na^{+} and SO^{2-} (Rasmussen et al., 2006; Figure 2). Many of these vary seasonally, thereby enabling annual ice layers to be determined with a high degree of precision. In the upper levels of Greenland ice cores, annual ice layers can be readily identified on the basis of the $\delta^{18}O$ record and seasonal variations in ice chemistry (Hammer et al., 1986; Meese et al., 1997). However, because of the relatively low accumulation rate at the NGRIP drill site, and the sensitivity of annual cycles in $\delta^{18}O$ to diffusion, NGRIP $\delta^{18}O$ data are not suitable for the identification of annual ice layers, and there are no continuous chemistry measurements with sufficiently high resolution for the determination of annual layers in the section of the NGRIP core back to c. 1405 m depth (10,227 yr). In order to obtain a complete Holocene chronology for NGRIP, therefore, it is necessary to link the early Holocene record with that from other Greenland core sites, Dye-3 and GRIP (Figure 1). The former is located in south-east Greenland where higher ice accumulation rate has enabled the best resolved of all the Greenland ice-core timescales for the mid- and late-Holocene to be constructed (Vinther et al., 2006). The Pleistocene-Holocene boundary cannot be accurately defined nor dated in that core, however, because of progressive ice-layer thinning due to the flow of the ice. Near the lower limit at which annual ice layers can be resolved in the Dye-3 core, there is a significant decline in $\delta^{18}O$ values to below normal Holocene levels that persists for a few decades. This marks the '8.2 ka cold event' that is also clearly recorded in the various proxy climate indicators in the NGRIP core (Thomas et al., 2007). In both Dye-3 and NGRIP, the $\delta^{18}O$ reduction marking the 8.2 ka event is also accompanied by a prominent ECM double peak and a marked increase in fluoride content. This represents the fall-out from a volcanic eruption, almost certainly on Iceland. The location of the double ECM peak inside the $\delta^{18}O$ minimum around 8000 yr BP constitutes a unique time-parallel marker horizon for correlating all Greenland ice-core records.

In the original Dye-3 core, the annual layer situated in the middle of the ECM double peak was dated at 8214 yr BP with an uncertainty of 150 yr (Hammer et al., 1986). Subsequent high-resolution analysis of the Dye-3 stable isotopes has enabled this age estimate to be considerably refined and it is now dated to 8236 yr b2k with a maximum counting error[1] of only 47 yr (Vinther et al., 2006). The term b2k refers to the ice-core zero age of AD 2000; note that this is 50 yr different from the zero yr for radiocarbon, which is AD 1950. Multi-parameter annual layer counting down from the 8236 yr double ECM horizon within the $\delta^{18}O$ minimum in the GRIP and NGRIP cores gives an age for the base of the Holocene, as determined by the shift in deuterium excess values, of 11,703 yr b2k with a maximum counting error of 52 yr (Rasmussen et al., 2006). The total maximum counting error (Dye-3 plus GRIP and NGRIP) associated with the age of the Pleistocene–Holocene boundary in NGRIP is therefore 99 yr, which is here interpreted as equivalent to a 2σ uncertainty. In view of the 99 yr uncertainty, however, it seems appropriate to assign an age to the boundary of 11,700 yr b2k. Accordingly, we recommend that the GSSP for the base of the Holocene be defined and dated at a depth of 1492.45 m in the Greenland NGRIP ice core.

Note 1: The uncertainty estimate of the GICC05 time scale is derived from the number of potential annual layers that the investigators found difficult to interpret. These layers were counted as 0.5

± 0.5 years, and the so-called maximum counting error (mce) is defined as one half times the number the these features. At the base of the Holocene, the mce is 99 years. Strictly speaking, the value of the mce cannot be intepreted as a standard Gaussian uncertainty estimate, but it is estimated that the true age of the base of the Holocene is within 99 yr of 11,703 yr b2k with more than 95% probability. For further discussion see Andersen et al. (2006).

References

American Commission on Stratigraphic Nomenclature. 1961. Code of Stratigraphic Nomenclature: American Association of Petroleum Geologists' Bulletin, 45, pp. 645–665.

American Commission on Stratigraphic Nomenclature. 1970. Code of Stratigraphic Nomenclature (2nd edition): American Association of Petroleum Geologists' Bulletin, 60, pp. 1–45.

Andersen, K.K., Svensson, A., Rasmussen, S.O., Steffensen, J.P., Johnsen, S.J., Bigler, M., Röthlisberger, R., Ruth, U., Siggaard-Andersen, M.-L., Dahl-Jensen, D., Vinther, B.M., Clausen, H.B. 2006. The Greenland Ice Core Chronology 2005, 15 – 42 ka. Part 1: Constructing the time scale. Quaternary Science Reviews, 25, pp. 3246–3257.

Björck, S., Walker, M.J.C., Cwynar, L.C., Johnsen, S. Knudsen, K-L., Lowe, J.J., Wohlfarth, B and INTIMATE Members. 1998. An event stratigraphy for the Last Termination in the North Atlantic region based on the Greenland ice-core record: a proposal from the INTIMATE group: Journal of Quaternary Science, 13, pp. 283–292.

Bowen, D.Q. 1978. Quaternary Geology: Pergamon Press, Oxford.

Dahl-Jensen, D.Gundestrup, N.S., Miller, O., Watanabe, O., Johnsen, S.J., Steffensen, J.P., Clausen, H.B., Svensson, A. and Larsen, L.B. 2002. The NorthGRIP deep drilling programme: Annals of Glaciology, 35, pp. 1–4

Grachev, A.M and Severinghaus, J.P. 2005. A revised + 10 ± 4°C magnitude of the abrupt change in Greenland temperature at the Younger Dryas termination using published GISP2 gas isotope data and air thermal diffusion constants: Quaternary Science Reviews, 24, pp. 513–519.

Hammer, C.U., Clausen, H.B. and Tauber, H. 1986. Ice-core dating of the Pleistocene/Holocene boundary applied to a calibration of the ^{14}C time scale: Radiocarbon, 28, pp. 284–291.

Johnsen, S.J., Dansgaard, W. and White, J.V.C. 1989. The origin of Arctic precipitation under present and glacial conditions: Tellus, 41B, pp. 452–468.

Johnsen, S., Dahl-Jensen, D., Gundestrup, N., Steffensen, J.P., Clausen, H.B., Miller, H., Masson-Delmotte, V., Sveinbjörnsdottir, A.E. and White, J. 2001. Oxygen isotope and palaeotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and northGRIP: Journal of Quaternary Science, 16, pp. 299–308.

Jouzel, J., Stiévenard, M., Johnsen, S.J., Landais, A., Masson-Delmotte, V., Sveinbjornsdottir, A., Vimeux, F., von Grafenstein, U. and White, J.W.C. 2007. The GRIP deuterium-excess record: Quaternary Science Reviews, 26, pp. 1–17.

Kleiven H.F., Kissel, C., Laj, C., Ninneman, U.S., Richter, T. and Cortijo, E. 2007. Reduced North Atlantic Deep Water coeval with Glacial Lake Agassiz fresh water outburst. Sciencexpress, 10.1126/science/1148924.

Lowe, J.J. and Walker, M.J.C. 2000.Radiocarbon dating the Last Glacial–Interglacial Transition (ca. 14–9 14C ka BP) in terrestrial and marine records: the need for new quality assurance protocols: Radiocarbon, 42, pp. 53–68.

Lowe, J.J., Rasmussen, S.O., Björck, S., Hoek, W.Z., Steffensen, J.P.,Walker, M.J.C., Yu, Z., the INTIMATE group, 2008. Precise dating and correlation of events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group: Quaternary Science Reviews 27, pp. 6–17.

Mangerud, J., Anderson, S.T., Berglund, B.E. and Donner, J.J. 1974. Quaternary stratigraphy of Norden: a proposal for terminology and classification: Boreas, 3, pp. 109–126.

Masson-Delmotte, V., Jouzel, J., Landais, A., Stievenard, M., Johnsen, S.J., White, J.W.C., Werner, M., Sveinbjornsdottir, A. & Fuhrer, K. 2005. GRIP deuterium excess reveals rapid and orbital-scale changes in Greenland moisture origin: Science, 209, pp. 118–121.

Meese. D.A., Gow, A.J., Alley, R.B., Zielinski, G.A. Grootes, P.M., Ram, M., Taylor, K.C., Mayewski, P.A. and Bolzan, J.F. 1997. The Greenland Ice Sheet Project 2 depth-age scale: methods and results: Journal of Geophysical Research, 102, pp. 26411–26423.

Morrison, R.B. 1969. The Pleistocene–Holocene boundary: Geologie en Mijnbouw, 48, pp. 363–372.

North Greenland Ice Core Project Members 2004. High-resolution record of Northern Hemisphere climate extending into the last interglacial period: Nature, 431, pp. 147–151.

Rasmussen, S.O., Andersen, K.K., Svensson, A.M., Steffensen, J.P., Vinther, B.M., Clausen, H.B., Siggaard-Andersen, M.L., Johnsen, S.J., Larsen, L.B., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M.E. and Ruth, U. 2006. A new Greenland ice core chronology for the last glacial termination: Journal of Geophysical Research, 111, DO6102, doi: 10,1029/2005JD006079.

Ruddiman, W.F. & Glover, L.K. 1975. Subpolar North Atlantic circulation at 9300 yr BP: faunal evidence: Quaternary Research, 5, pp.361–389.

Ruddiman, W.F. and McIntyre, A. 1981. The North Atlantic Ocean during the last deglaciation: Palaeogeography, Palaeoecology, Palaeoclimatology, 35, pp. 145–214.

Severinghaus, J.P., Sowers, T, Brook, E.J., Alley, R.B. and Bender, M.L. 1998. Timing of abrupt climate change at the end of the Younger Dryas interval from thermally fractionated gases in polar ice: Nature, 391, pp.141–146.

Thomas, E.R., Wolff, E.W., Mulvaney, R., Steffensen, J.P., Johnsen, S.J., Arrowsmith, C., White, J.W.C., Vaughn, B., Popp, T. 2007. The 8.2 ka event from Greenland ice cores: Quaternary Science Reviews, 26, pp. 70–81.

Vinther, B.M., Clausen, H.B., Johnsen, S.J., Rasmussen, S.O., Andersen, K.K., Buchardt, S.L., Dahl-Jensen, D., Seierstad, I.K., Siggard-Andersen, M.-L., Steffensen, J.P., Svensson, A. Olsen, J. & Heinemeier, J. 2006. A synchronized dating of three Greenland ice cores throughout the Holocene: Journal of Geophysical Research, 111, D13102, doi: 10,1029/2005JD006921.

Walker, M.J.C., Björck, S., Lowe, J.J., Cwynar, L.C., Johnsen, S., Knudsen K-L., Wohlfarth, B and INTIMATE group. 1999. Isotopic 'events' in the GRIP ice core: a stratotype for the Late Pleistocene: Quaternary Science Reviews, 18, pp. 1143–1151.

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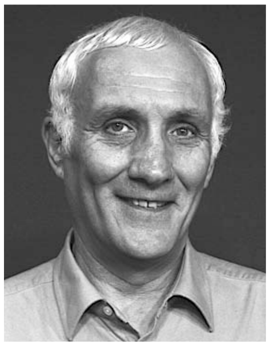

The Working Group *on the base of the Holocene is a Working Group of the Subcommission on Quaternary Stratigraphy and of INTIMATE (Integration of ice-core, marine and terrestrial records), which is itself a Working Group of the INQUA (International Union for Quaternary Research) Palaeoclimate Commission.*

Global launch event of the International Year of Planet Earth

UNESCO. Paris, 12–13 February 2008

The Global Launch Event of the International Year of Planet Earth (IYPE), proclaimed by the United Nations' General Assembly for 2008, took place on 12 and 13 February 2008 at the Paris headquarters of UNESCO.

The aim of this Event, involving input from all 68 IYPE national committees, was to put across the message of the International Year to decision makers and the public at large. We should all be making better use of the knowledge and outcomes of Earth science when framing planning and management decisions. Equally, we should all be using the skills and products of Earth science to influence the sustainable use of Earth resources, to make the world a healthier, wealthier and safer place for all.

Following the introduction of the events of the two-day celebration by the Master of ceremonies, Ted Nield (Geological Society of London and Chair of the IYPE Outreach Programme), Koïchiro Matsuura, Director-General of UNESCO addressed the audience of almost one thousand participants. Mr. Matsuura spoke of the fundamental role of the Earth sciences in securing a healthy Earth system that is vital to informed planning of sustainable development in the face of challenges—including climatic change.

He laid great emphasis on the serious implications of the fact that, in rich and poor countries alike, the numbers of students studying science are declining. This threat to the survival of university geology departments, if not reversed, will effectively cut off from society the Earth scientists of the future in a world in which the demand for sources of energy and raw materials will be with us for many decades to come as world population approaches nine billion.

In welcoming politicians, prominent members of geosciences institutions and leaders from within the business sector, he stressed the importance of the societal dependence on the Earth sciences on a day to day basis, so that while the Global Launch Event marks a peak achievement by the world's geoscientists, it constitutes only a starting point in improving understanding of the richness and diversity of Earth science by the global community.

Zhang Hongren (P. R. China), as President of the International Union of Geological Sciences (IUGS) and co-initiating organization of the International Year with UNESCO, spoke of the need for both leaders and public to make optimal use of the Earth sciences in protecting the Earth system. This is best done by adopting wise practices and protecting the Earth's inhabitants by using science to minimise the impact of both natural and human-induced risks.

Opening of the International Year of Planet Earth at UNESCO Headquarters, Paris, 12 February 2008.

The sustained efforts of the many scientists shouldering the burden of work for seven years to realize the IYPE in general and this event in particular were paid tribute to by Larry Woodfork, Chair of the International Year of Planet Earth Corporation. He emphasised the importance of the 10 geoscientific themes of the IYPE—Earth and Life; Climate; Health; Resources; Megacities; Geohazards; Groundwater; Soil; Deep Earth; and Ocean—and the potential of outreach activities that should extend well beyond the formal closure of the IYPE triennium in December 2009.

Jean-Pierre Jouyet, Minister of State in the French Ministry of Foreign and European Affairs, spoke to the effect that the twin facts of a changing climate and a burgeoning world population must be a priority for the French Presidency of the European Union in the second half of 2008. He noted the significant contribution already made to the IYPE by French geoscientists and wished the venture, which also marks the opening of the IYPE in France, every success.

There followed a number of short statements by government ministers and United Nations representatives. A clear awareness of the character of the IYPE and the need for outreach initiatives of this kind was evident in the statement by Tora Aasland, Minister of Research and Higher Education, Norway, who announced full commitment to, and considerable financial support for the activities of the IYPE in Norway, including support for the International Secretariat. In his five statements Hany Helal, Minister for Higher Education and Scienfitic Research of Egypt, endorsed this conceptual view. He shared with the audience Egypt's ambitions to arrive at 20% renewable energy in 2020 and a very significant ambition in energy savings.

The representative of the Minister for Higher Education, Science and Technology of the United Republic of Tanzania described the process of UN proclamation in which Tanzania played an initiating and decisive role. Also, the need of more geoscientific input in decision making in Africa was stressed and an invitation to participate in the African Launch Event to be held in Arusha, Tanzania, in May 2008 was extended to all. A statement on behalf of the Italian Minister of Environment, Land and Sea emphasized the full commitment and significant financial support provided by the Italian government. The representative went on to encourage nations to work on the IYPE legacy by stressing the need for realization of an international Research Centre on Earth sciences for sustainable development. A more wide-ranging discourse was presented by Arab Hoballah, Chief of the Sustainable Consumption and Production Branch of the Division of Technology, Industry and Economics of UNEP.

The scene then shifted from tributes, statements, explanations and ambitions to the ultimate example of a formal group letter of intent, called the *Paris Declaration*. The specific aims and objectives of the IYPE include urging decision makers the world over to make knowledge of Planet Earth freely available, to encourage development of new knowledge for the benefit of all nations, and to encourage support of the initiatives from all quarters of society so as to reduce natural hazard impact and guide sustainable development for generations to come (see page 270).

These aims are to be achieved by reviving and enhancing national educational systems and research capacity in Earth and space science institutions and universities; by producing global, digital and publicly available information on System Earth *via* projects such as "OneGeology" and "UN Spatial Data Infrastructure" (UNSDI); by promoting awareness of the structure, evolution, beauty and diversity of the Earth system and its human cultures inscribed in landscapes, through the establishment of "geoparks", biosphere reserves and World Heritage Sites as a public tool for conservation and development; by investing in Earth monitoring mechanisms as means of predicting large-scale changes in the Earth's spheres, using and enhancing existing global Earth observation systems; by producing books, DVDs and other media tools that will make Earth scientific knowledge much more accessible and provide a lasting legacy of the IYPE; and finally, by establishing an International Research Centre on Earth sciences for sustainable development.

After the UNESCO Director-General spoke about the IYPE's ambitious targets, Aubrey Manning (Emeritus Professor, renowned zoologist and television and radio broadcaster) enlivened the proceedings with a vision of the essentials of the Earth system.

The afternoon session began with the performance of a 'geo-song' called Mother Earth. This specially-composed item was sung with instrumental accompaniment by some 100 students who hailed from all continents of the world and were present as guests of the IYPE; they were selected from among the many students who participated in a world-wide Geo-Contest. The effort made by the members of the student choir, who had come together for the first time less than 24 hours before, was rewarded by the most enthusiastic applause of the day.

The remainder of the Launch Event was dedicated to a series of three themes of global concern. These sessions were led by renowned practitioners, from several walks of life, whose presentations provided the basis for interactive discussion with members of the audience.

Theme 1: Population growth and climate change: challenges for planet Earth

This theme was introduced by Aubrey Manning. The opening session included a presentation by Nikita White (Ireland), the first of three winners of a student competition involving original essays or poems—extracts from which prefaced the discussion of each theme. Views were then presented by Renate Christ, Secretary of the Intergovernmental Panel on Climate Change (IPCC), who gave a wide-ranging review of information indicative of anthropogenic influences leading to global warming. This was a stimulating if slightly harrowing overview, followed by an equally arresting but differently angled talk by Ghislain de Marsily of the French Academy of Sciences. The theme was then taken up by Ruud Lubbers, former Prime Minister of The Netherlands, followed by the views of Arti Mehra, mayor of the City of Delhi, India. Like Professor Lubbers who illustrated the theme from his personal experience of the remarkable growth of the city of Rotterdam, Ms. Mehta spoke from the point of view of one of the largest and fastest-growing cities in the world.

The day ended with a panel discussion, with audience questions directed at the four speakers, after which participants attended by invitation a glittering reception at the Hôtel de Ville, Paris, hosted by the Mairie de Paris.

The second day was opened by Mohammed Sheya, Minister Plenipotentiary of the United Republic of Tanzania. Professor Sheya, who more than anyone else ensured the successful passage of the 2008 Planet Earth resolution through the UN General assembly, emphasised the diverse ways in which scientific study of the Earth System bears upon human well-being. He noted that the physical laws that govern natural phenomena are being used with increasing effect to predict occurrences of natural disasters. Increasing partnerships between Earth scientists and social and environmental scientists have a critical role to play in enlightening politicians, policy- and decision-makers and the general public concerning global phenomena that impact upon the Earth system and their mitigation. Such collaboration also brings to light new possibilities of exploiting Earth's resources for the benefit of human-kind without causing harm to the Earth's ecological life support system.

Theme 2: Earth resources—threat or treat?

This theme was introduced by Marina Mielczarek, Grand Reporter of Radio France Internationale. First the floor was given to Hannah Lyn Creencia, a student from the Philippines who read an essay on the topic. An industrial standpoint on the theme was presented by Thierry Desmarest, Chair of the Board of Directors of Total (the world's fourth-biggest oil company), who predicted an increase of 1.2% per annum in energy demand over the next 25 years. Global demands and production of Earth materials were presented by Mark Myers, Director of one of the world's largest geoscientific research organisations, the US Geological Survey. Vice Minister Wang Shouxiang, of the Ministry of Land and Resources in China, described the rapidly growing need for Earth materials in his country. The following panel discussion was chaired by Marina Mielczarek, who also summed up the main strands of the session.

Theme 3: Geohazards: minimizing risk, maximizing awareness

After an introduction to geohazards by Marina Mielczarek and a poem presented by the third of the student competition winners, the South African Laura Byrne, views on this increasingly publicly prominent theme came from the world of insurance. Using an impressive collection of graphics, Peter Hoeppe, Head of the Geo Risks Research Department of the Munich Reinsurance Company, Germany, showed how hazard and risk are quantified as a means of assessing reinsurance cases in a competitive business environment.

The final scientific view on the theme was presented by Sospeter Muhongo, Director of the Regional Office for Africa of the International Council for Sciences (ICSU), South Africa, and the newly appointed Chair of the Science Programme of the IYPE. He considered a broad sweep of information and case studies bearing upon the theme, bringing together several perpectives. The succeeding panel discussion was a busy one and, before closing the third Session, a summary was presented by Marina Mielczarek.

The closing remarks of the UNESCO Director-General re-emphasized the pivotal importance of the Earth sciences in tackling the many challenges faced in the modern world, the value of Earth science data in anticipating and solving real life problems and the potential that Earth sciences possess for ensuring improved and sustainable management and planning by decision makers. Knowledge of the Earth system is humankind's insurance policy for the future. This theme ran through the recorded audio message of Sir Arthur C. Clarke which, in positive style, sent the delegates away with much to think about and an IYPE organisation optimistic about the taking up of its aims by industry, scientists and politicians. This Event served as a plaform from which other regional and national events will be launched around the world until the end of the IYPE triennium and beyond.

For more information about the IYPE Global Launch Event, please check: *www.yearofplanetearth.org/GLE*

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Declaration presented at the Global Launch Event of the International Year of Planet Earth (IYPE)

UNESCO, Paris, 12–13 February 2008

Preamble

Recalling that the General Assembly of the United Nations has declared 2008 as the International Year of Planet Earth;

Considering life depends on a self-sustaining Earth system that is unique, diverse and ever-changing;

Emphasizing that all decisions on global sustainability should be informed by the wealth of existing and potential Earth sciences' knowledge;

Noting that the wealth of Earth-sciences' related information available on issues like climate, water and other natural resources, energy, health, soils, the ocean, deep earth, natural hazards or life itself remain largely unknown to the public and often untapped by policy and decision makers;

Convinced that the IYPE and the Earth sciences can play a significant role in promoting the sustainable use of Earth resources and can provide valuable contributions to society through the UNESCO-led United Nations Decade of Education for Sustainable Development and the promotion of UN Millennium Development Goals, and

Persuaded that creating respect for Planet Earth, raising public awareness of the vulnerability and potential of the Earth's components and mitigating natural hazards will provide the basis for a more peaceful, prosperous and fulfilled community of nations;

Therefore, we

1. *Urge* decision makers of all nations to make freely available and utilize the wealth of knowledge about our Planet Earth and to encourage the development of new knowledge and technologies for the benefit of developing and developed nations alike;

2. *Encourage* Earth science communities, as well as public organizations and private industry, to support this initiative for the development of new knowledge and to develop strategies that will reduce the impact of natural hazards and guide sustainable development to meet the current needs of our expanding global society and of generations to come;

By

a. *Improving* access to Earth science knowledge through revised national educational systems and enhanced research capacity in Earth and Space Science institutions and universities;

b. *Producing* global, digital and publicly available information on System Earth such as “OneGeology” and “UN Spatial Data Infrastructure” (UNSDI) projects;

c. *Promoting* awareness of the structure, evolution, beauty and diversity of the Earth system and its human cultures inscribed in landscapes, through the establishment of “Geoparks”, biosphere reserves and World Heritage Sites as a public tool for conservation and development;

d. *Investing* in Earth monitoring mechanisms (both remote and in-situ) for the purpose of predicting large-scale changes in the Earth's spheres using and enhancing existing global Earth observation systems;

e. *Establishing* an International Research Centre on Earth sciences for sustainable development, and

f. *Producing* books, DVDs and other media tools that will make Earth scientific knowledge more accessible to the public and provide a lasting legacy for the IYPE.

IGCP Projects 2008

(OET—on extended term)

No. 475 Deltas in the Monsoon Asia-Pacific Region (DeltaMAP)
Project leaders: S. Goodbred, Jr. (USA), Y. Saito (Japan)
Duration: 2003–2007 (OET)
Website: http://unit.aist.go.jp/igg/rg/cug-rg/ADP/ADP_E/a_igcp475l_en.html

No. 478 Neoproterozoic-Early Palaeozoic Events in South-West-Gondwana
Project leaders: C. Gaucher (Uruguay), P. C. Boggiani (Brazil), A. Braun (Germany), H. Hartwig Frimmel (Germany), J.B. Germs (South Africa), D. G. Poiré (Argentina)
Duration: 2003–2007 (OET)
Official website: www.igcp478.com
Mirror website: www.vssagi.com/igcp478/igcp478.htm

No. 480 Tectonics of Central Asia
*Project leaders:*B. Natal'in (Turkey), A. Yin (USA), A. M. C. Şengör (Turkey), M. Kuzmin (Russia), Shuwen Dong (China)
Duration: 2005–2009
Website: http://www.igcp.itu.edu.tr/

No. 481 Dating Caspian Sea Level Change
Project leaders: S.B. Kroonenberg (Netherlands), S. Leroy (UK)
Duration: 2003–2007 (OET)
Website: http://www.caspage.citg.tudelft.nl www.caspiansealevelchange.org http://black.sealevel.ca

No. 486 Au-Ag-Telluride-Selenide Deposits
Project leaders: N. J. Cook (Norway), K. Kojonen (Finland)
Duration: 2003–2007 (OET)
Website: www.ngu.no/igcp486

No. 487 Seismic Microzoning of Latin American Cities
Project leaders: J. L. Alvarez Gómez (Cuba), A. A. Giesecke Matto (Peru), G. F. Panza (Italy)
Duration: 2004–2008
Website: www.ictp.trieste.it/~sand/SMLAC/SMLAC.html

No. 493 The Rise and Fall of the Vendian Biota
Project leaders: M. Fedonkin (Russia), P. Vickers-Rich (Australia), J. Gehling (Australia)
Duration: 2003–2007 (OET)
Website: http://www.geosci.monash.edu.au/precsite

No. 495 Quaternary Land–Ocean Interactions
Project leaders: A. Long (UK), S. Islam (Bangladesh)
Duration: 2004–2008
Website: www.geography.dur.ac.uk/projects/igcp495

No. 497 The Rheic Ocean
Project leaders: U. Linnemann (Germany), R. D. Nance (USA), M. de Wit (South Africa), E. Bozkurt (Turkey), P. Kraft (Czech Republic), F. Pereira (Portugal), R. A. Strachan (UK)
Duration: 2004–2008
Website: http://www.snsd.de/igcp497/

No. 499 Devonian Land–Sea Interaction: Evolution of Ecosystems and Climate in the Devonian
Project leaders: P. Königshof (Germany), J. Lazauskiene (Lithuania), E. Schindler (Germany), Volker Wilde (Germany) and N. Yalçin (Turkey)
Duration: 2004–2008
Website: http://www.senckenberg.de/igcp-499

No. 500 Dryland Change: Past, Present, Future
Project leader: D.Thomas (UK)
Duration: 2004–2008
Website: http://igcp500.ouce.ox.ac.uk/

No. 502 Global Comparison of Volcanic-hosted Massive Sulphide Districts
Project leaders: R.Allen (Sweden), F. Tornos (Spain), J. Peter (Canada), N. Çagatay (Turkey)
Duration: 2004–2008
Website: http://www.1tu.se/tkg/ http://www.1tu.se/tkg/avd/kgo/forsk/IGCP

No. 503 Ordovician Palaeogeography and Palaeoclimate
Project leaders: T. Servais (France), D.A.T. Harper (Denmark), J. Li (China), A. Munnecke (Germany), A. W. Owen (UK), P.M. Sheehan (USA)
Duration: 2004–2008
Website: http://sarv.gi.ee/igcp503/

No. 506 Marine and Non-marine Jurassic
Project leaders: Jingeng Sha (China), Nicol Morton (France), W. A.P. Wimbledon (UK), Paul E. Olsen (USA), Alberto G. Riccardi (Argentina), Grzegorz (Gregory) Pieñkowski (Poland), Yongdong Wang (China)
Duration: 2005–2006 (2009)
Website: http://www.nigpas.ac.cn/IGCP506 index.asp

No. 507 Paleoclimates of the Cretaceous in Asia
Project leaders: Yong Il Lee (Korea), Xiaoqiao Wan (China), Takashi Sakai (Japan), and Krishnan Ayyasami (India)
Duration: 2006–2010
Website: http://igcp507.kopri.re.kr/

No. 509 Palaeoproterozoic Supercontinents and Global Evolution
Project leaders: S.M. Reddy (Australia), D. Evans (USA), R. Mazumder (India)
Duration: 2005–2009
Website: http://earth.geology.yale.edu/igcp509/

No. 510 A-type Granites and Related Rock through Time
Project leaders: Roberto Dall'Agnol (Brazil), Carol D. Frost (USA), O. Tapani Rämö (Finland), L.J. Robb (South Africa)
Duration: 2005–2009
Website: http://www.igcp-510.org

No. 511 Submarine Mass Movements and their Consequences
Project leaders: Jacques Locat (Canada), Juergen Mienert (Norway) and Roger Urgeles (Spain)- (IOC link)
Duration: 2005–2009
Website: http://www.geohazards.no/IGCP511

No. 512 Neoproterozoic Ice Ages
Project leaders: Graham A. Shields (Australia), Emmanuelle Arnaud (Canada)
Duration: 2005–2009
Website: www.IGCP512.org

No. 513 Karst Aquifers and Water Resources
Project leaders: Chris Groves (USA), Yuan Daoxian (China), Bartolome Andreo-Novarro (Spain), Heather Viles (UK)
Duration: 2005–2009
Website: http://hoffman.wku.edu/igcp/513.html (General information) http://hoffman.wku.edu/karst2007/k2007.html http://www.wku.edu/cehp http://www.cosis.net/members/meetings/sessions/information.php?p_id=247&s_id=4433

No. 514 Fluvial Palaeosystems: Evolution and Mineral Deposits
Project leaders: N. Patyk-Kara (Russia), A. Duk-Rodkin (Canada), Baohong Hou (Australia), Li Ziying (China), Vladimir Dolgopolov (Kazakhstan)
Duration: 2005–2009
Website: http://www.igem.ru/igcp514/

No. 516 Geological Anatomy of East and South East Asia
Project leaders: Ken-ichiro Hisada (Japan), Punya Charusiri (Thailand), Byung-Joo Lee (Rep. of Korea), Xiaochi Jin (China)
Duration: 2005–2009
Website: http://staff.aist.go.jp/hara-hide/igcp516

No. 519 Hydrogeology, Hydrochemistry and Management of Coastal Aquifers on the Atlantic Coast of South America
Project leaders: Emilia Bocanegra (Argentina), Emilio Custodio (Spain), Marisol Manzano (Spain), Gerson Cardoso (Brazil), Jenny Reynolds Vargas (Costa Rica)
Duration: 2005–2009
Website: http://www.mdp.edu.ar/exactas/geologia/cgcyc/hidrogeologia.html

No. 521 Black sea Mediterranean Corridor during the last 30 ky: Sea level change and human adaptation
Project leaders: Valentina Yanko-Hombach (Canada), Yucel Yilmaz (Turkey), Pavel Dolukhanov (UK)
Duration: 2005–2009
Website: http://www.avalon-institute.org/IGCP
http://black.sealevel.ca
http://www.bridge.bris.ac.uk/projects/EMBSECBIO
http://www.paleontol.geo.sfedu.ru

No. 523 GROWNET—Gobal Ground Water Network
Project leaders: Shrikant Daji Limaye (India), Antony J Reedman (UK)
Duration: 2005–2009
Website: http://www.igcp-grownet.org

No. 524 Arc-Continent Collision
Project leaders: Denis Brown (Spain), Chi-Yue Huang (Taiwan)
Duration: 2007–2009
Website: www.ija.csic.es/gt/IGCP524

No. 526 Risks Resources and Record of the Past on the Continental Shelf
Project leaders: Francesco L.atino Chiocci (Italy), Lindsay Collins (Australia), Michel Michaelovitch de Mahiques (Brazil), Renée Hetherington (Canada)
Duration: 2007–2011

No. 529 Availability of groundwater resources in selected urban areas in Southern African Development Community (SADC) region
Project leaders: Imasiku A. Nyambe (Zambia)
Duration: 2007–2011

No. 540 Gold-bearing hydrothermal fluids of oregenic deposits
Project leaders: P.S. Garofalo (Italy), J.R. Ridley (USA), Vsevolod Prokof'ev (Russia)
Duration: 2007–2011
Website: http://www.geomin.unibo.it/igcp_540

No. 543 Low-temperature thermochronology: applications and inter-laboratory calibration
Project leaders: Massimiliano Zattin (Italy), J. I. Garver (USA), Vitaliy A. Privalov (Ukraine), Alexei V. Soloviev (Russia), Cornelia Spiegel (Germany), Maarten de Wit (South Africa), Dewen Zheng (China)
Duration: 2007–2010

No. 545 Clays and clay minerals in Africa
Project leaders: Georges-Ivo E. Ekosse (South Africa)
Duration: 2007–2011
Website: http://www.saweb.co.za/claymineralsafrica/

No. 546 Subduction zones of the Caribbean
Project leaders: Antonio Garcia-Casco (Spain), Uwe Martens (USA)
Duration: 2007–2011
Website: http://www.ugr.es/~agcasco/igcp546/

No. 555 Rapid Environmental/Climate Change in the Cretaceous Greenhouse World
Project leaders: Chengshan Wang (China), Robert Scott (USA), Hugh Jenkyns (UK), Michael Wagreich (Austria), William Hay (USA); Zakharov Y.D. (Russia)
Duration: 2007–2010
Website: www.cretaceousworld.com/igcp555

No. 557 Diamonds, xenoliths and kimberlites
Project leaders: Holger Sommer (Botswana), Klaus Regenauer-Lieb (Australia), Christoph Hauzenberger (Austria) Jonathan Kashabano (Tanzania), Gétan Moloto-A-Kenguemba (Central African Republic)
Duration: 2007–2011
Website: http://igcp557.uni-graz.at/

No. 559 Crustal Architecture and landscape Evolution
Project leaders: Bruce R. Goleby (Australia) and 14 members (USA, Canada, China, Finland, Netherlands, New Zealand, Russia)
Duration: 2008–2012

No. 565 Geodetic Monitoring of the Global Water Cycle
Project leaders: Hans-Peter Plag (USA), Richard S. Gross (USA), Markus Rothacher (Germany), Norman L. Miller (USA), Susanna Zerbini (Italy), Chris Rizos (Australia)
Duration: 2008–2012

No. 567 Earthquake Archaeology –Archaeoseismology along the Alpine-Himalayan seismic zone
Project leaders: Manuel Sintubin (Belgium), Iain Stewart (UK), Tina Niemi (USA), Erhan Altunel (Turkey)
Duration: 2008–2012

No. 572 Permian-Triassic Ecosystems
Project leaders: Zhong Qiang Chen (Australia), Richard J. Twitchett (UK), Jinnan Tong (China), Margret L. Fraiser (USA), Sylvie Crasquin (France), Steve Kershaw (UK), Thomas J. Algeo (USA), Kliti Grice (Australia)
Duration: 2008–2012

Funded projects	33
O.E.T.	5
Total	38

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New IGCP Projects accepted and starting in 2008

Project No. 559 Crustal Architecture and Landscape Evolution
Countries involved: Australia, Canada, China, Finland, Japan, Netherland, New Zealand, Russia, South Africa, Spain, USA
Full title: Crustal Architecture and Images—Structural controls on landscape, resources and hazards
Project leaders: Dr. Bruce R. Goleby (Australia)
Duration: 2008–2012
Contact: Dr. Bruce R. Goleby, Geoscience Australia, GPO Box 378, Canberra ACT 2601, Australia, Tel: + 61 2 6249 9404, Fax: + 61 2 6249 9972, E-mail: bruce.goleby@ga.gov.au

This project will focus on that part of planet Earth that has the most significance for the world's communities, namely the Earth's crust, that outer part of the planet on which we all live. The project will make available to communities-at-large a wealth of information and seismic imaging that is commonly only available to research workers but yet has a profound effect on how we think of the landscapes, natural environments and their controlling geological processes and tectonic influences.

An understanding of crustal architecture and tectonic history/processes is fundamental to any appreciation and understanding of landscapes, surface geology and natural hazards at a local, regional and global scale.

The project aims to bridge the gap between scientific effort and the public interest and give a real insight into nature of the major geological processes in the outer 50–70 km of the Earth that directly affects our lives.

Through the project's web site development phase, it will link and archive images and sources of information on crustal architecture from world-wide seismic imaging programs. Through the sponsorship of key international symposia the project will foster international cooperation and knowledge transfer.

The project has widespread relevance to decision making in the areas of natural resource development, urban and national infrastructure planning, university teaching, groundwater management and natural hazards assessment on all continents.

Project No. 565 Geodetic Monitoring of the Global Water Cycle
Countries involved: Germany, Italy, Republic of Korea, South Africa, USA
Full title: Developing the Global Geodetic Observing System into a Monitoring System for the Global Water Cycle
Project leaders: Prof. Dr. Hans-Peter Plag (USA), Dr. Richard S. Gross (USA), Prof. Dr. Markus Rothacher (Germany), Prof. Norman L. Miller (USA), Prof. Susanna Zerbini (Italy), Chris Rizos (Australia)
Duration: 2008–2012
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Water is essential to life and central to human welfare, progress and sustainable economic growth. The global hydrological cycle operates on a continuum of temporal and spatial scales. Its variability which regulates flood, drought, and disease hazards is being continuously transformed by climate change, erosion, pollution, agriculture, and civil engineering practices. Despite its fundamental role for mankind, and despite the challenges through increasingly limited availability of water for human activities, knowledge of key quantities of the hydrological cycle is still associated with large uncertainties, and urgent questions cannot be answered.

Geodetic observations relate to the Earth's gravity field, shape, and rotation and their changes in time (the three fundamental areas of geodesy). At time scales from weeks to decades, hydrological loading of the Earth's surface dominates non-secular variation in each of these areas of geodesy. Thus, geodesy naturally provides integral constraints on the water cycle at multiple spatial and temporal scales. Space-geodetic sensors capture the signals of variation in the entire fluid envelope of the solid Earth, including the terrestrial water storage. Space geodetic observations of surface mass variability are inherently strong at regional to global scales, and could be an important complement to traditional in-situ measurements of terrestrial water storage.

The Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) has the capability to monitor mass transport in the Earth system and particularly the global water cycle. Crucial to this application are the gravity satellite missions that measure the temporal variability of the Earth's gravity field. The GRACE mission has demonstrated the great potential of these missions, but the continuity of the satellite missions is not secured. Moreover, the utilization of the full suite of the geodetic observations is hampered by model insufficiencies, inconsistencies, and a lack of integration of the different space-geodetic techniques. As a consequence, the dissemination of products into practical water management has not taken place.

The proposed project aims to develop GGOS into a monitoring system for the hydrological cycle on global to regional scales. The intergovernmental and international frames of the Group on Earth Observation (GEO) and GGOS, respectively, will be used to ensure sufficient satellite gravity missions, particularly with participation of emerging space agencies in Africa and Asia. Ongoing and planned research will: address the combination of space-geodetic observations, particularly GPS and GRACE-type observations, in order to exploit their individual strengths and mitigate their weaknesses; improve the geophysical models for the processing of the observations; enhance the extraction of highly accurate information on changes in terrestrial water storage, prepare the assimilation of the observations in integrated predictive models of the hydrological cycle, and focus on the interpretation of the space-geodetic observations in terms of regional groundwater and soil moisture changes.

Through cooperation with research institutions in developing countries, the project will support capacity building in the field of space-geodetic data processing, modeling of the hydrological cycle, and interpretation of the observations in terms of terrestrial water storage. Through interaction with water management authorities particularly in developing countries, the practical use of the products for regional water management will be promoted. Coordination of the research and capacity building will be provided through a series of five annual workshops, with the first one focusing on satellite gravity missions, a second and third one on data processing, technique integration, modeling and interpretation, and the last two on hydrological applications, particularly in developing countries. Expected results are an improved understanding of mass redistribution in the water cycle, in particular, changes in groundwater; better exploitation of the space-geodetic observations for hydrology; and societal benefits through an improved knowledge basis for regional water management.

Project No. 567 Earthquake Archaeology
Countries involved: Armenia, Austria, Belgium, Canada, France, Germany, Greece, India, Israel, Italy, Japan, Jordan, Kyrgyzstan, Spain, Turkey, UK, USA, Venezuela
Full title: Earthquake Archaeology: Archaeoseismology along the Alpine–Himalayan seismic zone
Project leaders: Prof. Dr. Manuel Sintubin (Belgium), Dr. Iain Stewart (USA), Prof. Dr. Tina Niemi (USA), Prof. Dr. Erhan Altunel (Turkey)
Duration: 2008–2012
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How can planners and politicians prepare for earthquakes? Damaging earthquakes on fault lines typically recur at intervals of centuries to millennia but the seismographs that register them have only been around for about hundred years. To reduce the hazard from earthquakes we need a longer record of them than can be provided from such instruments. On the assumption that future earthquakes will be like those of the geologically recent past, we need to look back in order to forecast forward. Archaeological evidence is especially valuable for determining earthquake activity over millennial time spans, especially where integrated with historical documents and geological evidence.

Archaeology can be used in three ways to help confront the seismic-hazard threat.

1) First, where archaeological relics are displaced they can be used to find earthquake faults, show in which direction they slipped during the earthquake and from these cultural 'piercing points' establish comparative fault slip-rates.
2) Second, archaeological information can date episodes of faulting and shaking, with some cultural artifacts (e.g., epigraphic or numismatic (coins) data, pottery typology) yielding age estimates more precisely than high-resolution geological stratigraphies.
3) Third, we can search for ancient signs of seismic damage. The obvious difficulty with the last approach is that it is hard to distinguish between damage caused by an earthquake and that caused by another destructive event, such as war or the natural failure of foundations.

Typologies of earthquake-characteristic damage have been proposed—most based on inferences drawn from seismic damage to modern constructions but some derived from engineering analysis of ancient structures—but rarely have they been subjected to a critical and systematic analysis. Consequently 'archaeoseismic indicators' are accepted by some earthquake scientists and rejected by others.

An important element of this project will be to go from the shaking table to the archaeological remains in developing a broadly accepted methodological framework to what reliably constitutes seismic damage. The key element of this project is our contention that archaeological evidence has the potential to make a valuable contribution to long-term seismic-hazard assessment in earthquake-prone regions where there is a long and lasting cultural heritage. We have identified the Alpine–Himalayan region as the ideal laboratory, because the archaeoseismological studies that have already taken root in the Eastern Mediterranean can be extended to neighbouring regions, most importantly south along North African shores, north into the Caucasus Mountains, and east into western Asia. As well as trying to establish a common methodological framework that is crucial for archaeoseismology to develop into a recognized and legitimate field of earthquake science, case studies from these regions will address specific questions relating to the locations, timing and size of past destructive earthquakes and so will aim to contribute specific information for seismic hazard analysis.

But there is a wider remit for our activities, because our research clearly has important humanitarian and economic implications. As illustrated by the 2003 collapse of the World Heritage site in the Bam (Iran) earthquake, cultural heritage sites themselves are threatened by seismic destruction. Clearly, there is a growing need to understand how ancient structures and monuments respond to faulting and ground shaking. On an even broader scale, our work will contribute to our understanding of ancient history, elucidating why some cities were abandoned or why former societies suffered decline, and confronting the enduring attraction of fault lines in luring peoples, ancient and modern, to settle along persistent danger zones. In other words, this project will contribute to our own cultural heritage.

Project No. 572 Permian-Triassic Ecosystems

Countries involved: Argentina, Australia, Austria, Canada, China, Croatia, Czech Republic, France, Germany, Hungary, India, Iran, Israel, Italy, Japan, New Zealand, Norway, Poland, Romania, Russia, Slovenia, Spain, Thailand, Turkey, Switzerland, UK, USA

Full title: Restoration of marine ecosystems following the Permian-Triassic mass extinction: Lessons for the present

Project leaders: Zhong Qiang Chen, Dr. Richard J. Twitchett, Dr. Jinnan Tong, Dr. Margret L. Fraiser, Dr. Sylvie Crasquin, Dr. Steve Kershaw, Dr. Thomas J. Algeo, Dr. Kliti Grice

Duration: 2008–2012

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Many marine ecosystems are under threat at the present day. This is nothing new, as the marine realm has suffered major extinction and upheaval on numerous occasions over the geological past, the most serious of which occurred during the Permian-Triassic transition. Of the major factors supposed to have caused the Permian-Triassic biotic crisis, such as increased carbon dioxide concentrations, oceanic anoxia, hypercapnia (CO_2 poisoning) and rapid global warming, some are observed in the present day, and others may happen in the near future. The Permian-Triassic rock and fossil records may thus record a natural experiment in global-scale ecosystem collapse that, if properly deciphered, could provide an insight into the possible responses of modern marine ecosystems to present day climate and environmental change. This links into current global concerns and issues such as the "sustainable use of global biodiversity", "biodiversity response to global warming" and "keeping our planet environmentally sustainable".

The proposal aims to investigate the recovery of marine ecosystems following the Permian/Triassic (P/Tr) mass extinction through analyses of the rock and fossil records of South China, Tibet, elsewhere in Asia, eastern Europe, Russia, Japan, Canada, Greenland, Spitsbergen, western US, western Australia and New Zealand. Through detailed studies of Early Triassic biostratigraphy, palaeontology, palaeoecology, sedimentology, geochemistry and biogeochemistry in the above regions, this project will attempt to formulate recovery patterns of various fossil groups; to reconstruct the global Early Triassic oceanic and climatic conditions; to construct a database of P/Tr ecosystem types; and to correlate all of this data in a global stratigraphic framework. Ultimately, this project will reveal the patterns and processes of marine ecosystem restoration following the P/Tr mass extinction; will elucidate the factors controlling the recovery rates of marine communities in various habitats and climate zones; will determine the similarities and differences in the responses of different marine groups to biotic crisis; and will assess the effects of climate or other geological events on the restoration of the defaunated marine ecosystems.

These goals will be achieved primarily by collaborative fieldwork in key Early Triassic successions in more than 10 different countries over five years and related laboratory work in over 20 different countries. The results of our project, which are to be published in four edited books and special volumes, in international peer-reviewed journals, in annual symposium proceedings and on the world-wide-web, will advance scientific understanding of the interactions between the biosphere and geosphere and lead to a better understanding of ancient defaunation events. The firm support and active involvement in this project of most top scientists in this field from around the world will lead to unique training opportunities for postgraduate students from a range of countries (Argentina, Austria, Australia, Canada, China, Japan, France, Germany, Iran, India, Switzerland, UK, USA) as well as professionals from developing and developed regions alike. As a result, the proposed project will provide a friendly platform for participants to communicate their own research results and also bring together global experts, and research facilities to solve a truly global-scale problem. The competitive track records of the proposers underscore this project's high chance of academic success as well as its potential to achieve significant societal benefits in the form of knowledge sharing and enhanced scientific cooperation between nations.

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