Global chronostratigraphical correlation table for the last 2.7 million years, v. 2016a

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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 IUGS 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). Previous versions of the chart (see websites[1]) were published as Gibbard *et al*. (2004, 2005) and Gibbard & Cohen (2008). Since then semi-annually updated versions have appeared on the web (e.g. Cohen & Gibbard, 2010). A major update is in progress. This 2016a version is a minor update, prepared for the 35th International Geological Congress held at Cape Town, South Africa from August 27th to September 4th 2016.

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 (Cohen *et al.*, 2013). At present the Subseries (Subepoch) divisions of the Pleistocene are not formalised. Series, and thereby systems, are formally-defined based on Global Stratotype Section and Points (GSSP) of which two divide the Quaternary System into the Holocene and Pleistocene Series. The formal base of the Pleistocene, as ratified in 2009, coincides with a GSSP at Monte San Nicola in southern Italy, marking the base of the Gelasian Stage (Rio *et al.*, 1994, 1998). The Gelasian GSSP at 2.58 Ma replaces the previous Pleistocene base GSSP (~1.8 Ma, defined at Vrica, southern Italy), following 60 years of discussion in international stratigraphical commissions and congresses. However, the latter continues as the GSSP for the base of the Calabrian Stage. The chart extends to 2.7 million years to include the very end of the preceding Piacenzian Stage of the Pliocene Series.

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 (Cita, 2008), and even earlier cooling events are known from the Pliocene. The closure of Central American Seaways between the Pacific and Atlantic ocean, in three steps starting 3.2 Ma, significantly restructured oceanic and atmospheric circulation on the Northern Hemisphere, causing increased high latitude precipitation, freshening of the Arctic Ocean and increased sea-ice cover amplifying cooling through albedo feedbacks (Bartoli *et al.*, 2005; Lunt *et al.*, 2007; Sarnthein *et al.*, 2009). Fully completed Panama Isthmus closure by 2.7 Ma is believed to explain the palaeoenvironmental transitions observed at the Pliocene-Pleistocene boundary and to have culminated in the Quaternary glacial-interglacial oscillating climate mode. Since its definition at 1.8 Ma there had been strong pressure for the basal Quaternary / Pleistocene boundary to be moved downwards better to reflect the initiation of major global cooling (Pillans and Naish 2004; Gibbard *et al.* 2005; Bowen & Gibbard 2007; Cita & Pillans, 2010), effectively corresponding to the Gauss / Matuyama magnetic Chron boundary (e.g. Partridge, 1997; Suc *et al*., 1997). See also: Ogg & Pillans (2008); Head *et al.* (2008); Lourens (2008); Gibbard & Head (2009a, b) and Gibbard *et al.* (2009).

Pleistocene GSSPs

Formal GSSPs for the Pleistocene Subseries will be proposed shortly. 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 two candidate sections are being considered by an ICS Working Group (Head *et al.*, 2008). Following recent re-evaluation, the Middle –

[1] http://www.quaternary.stratigraphy.org.uk/charts; also at: www.stratigraphy.org and www.inqua-saccom.org

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, 2008).
The start of the Eemian in NW Europe (defined on pollen biostratigraphy) lags the start of MIS 5e by a few 1000 years (Sánchez-Goñi et al., 1999; Sier et al., 2015). Establishing the exact lag time is an important current research goal, tying global sea-level, ice-mass and crustal glaciohydro-isostasy studies with regional climatic variation, oceanography and palaeomagnetics (e.g. Shackleton et al., 2003; Lourens, 2004; Lambeck et al., 2006; Sier et al., 2015). Accurate age-control on the timing of the Eemian and the relation to MIS 5e is important as it is frequently used to deduce background tectonic uplift/subsidence rates, which is in turn input sea-level rise and glacio-isostatical adjustment studies for the Late Pleistocene and Holocene (e.g. Dutton & Lambeck, 2012; Dutton et al. 2015). Accurate age-control on the last interglacial is also of importance as input to astronomically tuned timescales that in the Quaternary are used for the Middle and Early Pleistocene (e.g. Head et al. 2008) and in the Neogene, Paleogene and beyond (Lisiecki and Raymo, 2005).

The Holocene is generally regarded as having begun 10,000 radiocarbon years before 1950 AD, or 11.7k calendar years before 2000 AD (cf. Wolff, 2008). This boundary has been defined as a Global Stratotype Section and Point (GSSP) in the North-GRIP ice core of the Greenland Ice-Core Project (NGRIP: Rasmussen *et al.*, 2006; Walker *et al.*, 2008, 2009; Hoek, 2008). Auxiliary stratotypes are also defined, for example, in an annually-laminated lake sequence in western Germany (Litt *et al*., 2001). The Holocene Series is not divided into named stages, however, at the time of writing formal definition of stage subdivisions is under consideration by the ICS. At the same time ICS are discussing the possibility of formalising the definition of subseries for the same period (Early, Middle and Late Holocene cf. Walker *et al*. 2012).

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 stratigraphy is taken from oxygen isotope data obtained from tests of fossil benthonic (ocean-floor dwelling) foraminifera, retrieved from deep-ocean cores from 57 locations around the world. The plots depict $\delta^{18}O$ (the ratio of ^{18}O *versus* ^{16}O) of a stacked record as processed by Lisiecki and Raymo (2005). Their calibrated ages for the last seven major glacial terminations are included. The inventory of geomagnetic chrons, subchrons and excursions on the chart, is taken from the compilation of Lai & Channell (2007: their Tables 2 and 3). Geomagnetic excursions and reversals occur at times of low magnetic field intensity and their ages are updated after Channell *et al.* (2009; 2016). Shifts in this ratio are a measure of global ice-volume, 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 time (i.e. Paleogene, Neogene), has been advocated on occasions. The only succession that has been divided in this way is the shallow marine sequence 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) (cf. also Cita & Pillans, 2010). In view of their duration, covering 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'.

Early–Middle Pleistocene transition ('mid-Pleistocene revolution')

The chart shows the time between c. 1.2 and 0.5 Ma to have been a transition period in which low-amplitude 41-ka obliquity-forced climate cycles of the earlier Pleistocene were replaced progressively by high-amplitude 100-ka cycles. These later cycles are indicative of slow ice build-up and subsequent rapid melting, and imply a strongly non-linear forced climate system compared to before, accompanied by substantially increased global ice volume during glacials after 940 ka. The Early-Middle Pleistocene transition, through the increased severity and duration of cold stages, had a profound effect on the biota and the physical landscape, especially in the northern hemisphere (Head & Gibbard 2005). Orbital and non-orbital climate forcing, palaeoceanography, stable isotopes, organic geochemistry, marine micropalaeontology, glacial history, loess–palaeosol sequences, pollen analysis, large and small mammal palaeoecology and stratigraphy, and human evolution provide a series of discrete events identified from Marine Isotope Stage (MIS) 36 (c. 1.2 Ma) to MIS 13 (c. 540–460 Ma). Of these, the cold MIS 22 (c. 880–870 ka) is the most profound. On this basis Head & Gibbard (2005) and Head *et al.* (2008), following earlier suggestions (e.g. Richmond 1996), concluded that on practical grounds the Matuyama–Brunhes palaeomagnetic Chron boundary (mid-point at c.773-4 ka, with an estimated duration of 7 ka; within MIS 19; Channell *et al.* 2004; Channell *et al.* 2008) is the best overall point for establishing the Early–Middle Pleistocene Subseries boundary.

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 (units S0 to S32) for the Jingbian site in northern China (Ding *et al.,* 2005). High values of magnetic susceptibility indicate repeated episodes of weathering (soil formation), predominantly in interglacials with relative strong summer monsoon. In intercalated strata (units L1 to L33; accumulated during glacials) the proportion of coarser grains (grains > 63 μm, % dry weight) is a signal of progressive desertification in Central Asia. The magnetic and grain-size data is plotted on the Chinese Loess Particle Time Scale (Ding *et al.*, 2002). Alternating loess-palaeosol sequence accumulation throughout NE China coincides with the begin of the Pleistocene and buries the more intensively weathered Pliocene ‘Red Clay’ Formation (An Zhisheng *et al.*, 1990).

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), mimicked in other proxy-records from the lake (e.g. Prokopenko et al., 2010, exemplified for MIS 11). The composite biogenic silica record from cores BDP-96-1, -96-2 and -98 is plotted on an astronomically tuned age-scale (above 1.2 Ma: Prokopenko et al., 2006; below 1.2 Ma: Prokopenko & Khursevich, 2010).

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 from the Stratigraphy of the USSR: Quaternary System (1982, 1984), Krasnenkov et al. (1997), Shik et al. (2002), Danukalova (pers. comm.), Gerasimenko (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 (pers. comm.). The New Zealand stages are from Pillans (1991) and Beu (2004).

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