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An optimized scheme of lettered marine isotope substages for the last 1.0 million years, and the climatostratigraphic nature of isotope stages and substages

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Abstract :

A complete and optimized scheme of lettered marine isotope substages spanning the last 1.0 million years is proposed. Lettered substages for Marine Isotope Stage (MIS) 5 were explicitly defined by Shackleton (1969), but analogous substages before or after MIS 5 have not been coherently defined. Short-term discrete events in the isotopic record were defined in the 1980s and given decimal-style numbers, rather than letters, but unlike substages they were neither intended nor suited to identify contiguous intervals of time. Substages for time outside MIS 5 have been lettered, or in some cases numbered, piecemeal and with conflicting designations. We therefore propose a system of lettered substages that is complete, without missing substages, and optimized to match previous published usage to the maximum extent possible. Our goal is to provide order and unity to a taxonomy and nomenclature that has developed ad hoc and somewhat chaotically over the decades. Our system is defined relative to the LR04 stack of marine benthic oxygen isotope records, and thus it is grounded in a continuous record responsive largely to changes in ice volume that are inherently global. This system is intended specifically for marine oxygen isotope stages, but it has relevance also for oxygen isotope stages recognized in time-series of non-marine oxygen isotope data, and more generally for climatic stages, which are recognized in time-series of non-isotopic as well as isotopic data. The terms “stage” and “substage” in this context are best considered to represent climatostratigraphic units, and thus “climatic stages” and “climatic substages”, because they are recognized from geochemical and sedimentary responses to climate change that may not have been synchronous at global scale.

Highlights

► We define lettered MIS substages for past 1.0 million years relative to LRO4. ► Contradictions and gaps exist among previous *ad-hoc* designations of substages. ► Many marine isotope substages have been defined relative to non-marine records. ► This scheme of substages is complete and maximally consistent with earlier efforts. ►Marine isotope stages and substages are climatostratigraphic, not geochronologic.

Keywords : Substages, Stages, Marine isotope stages, MIS, Chronology, Chronostratigraphy, Climatostratigraphy

1. Introduction

As the complex history of Quaternary glaciation, climate, sea level, and ocean circulation has become apparent over the past 60 years, the scientific community has developed a variety of systems to identify intervals of time and glacio-climatic events. One of the most widely applied systems has been that of numbered marine oxygen isotope stages, or more generally oxygen isotope stages, moving from the Holocene back in time as MIS 1, MIS 2, MIS 3, etc., where "MIS" refers to "marine isotope stage". These isotope stages have been divided in some cases into lettered substages, most notably in MIS 5 as substages MIS 5a, 5b, 5c, 5d, and 5e, which were formally defined as such by Shackleton (1969). In the past 20 years, many publications have used lettered substages for intervals outside MIS 5, from MIS 2a (Yelovicheva, 2006) to at least MIS 19c (Tzedakis et al., 2012a,b). However, these lettered substages other than those of MIS 5 have been named in many different papers, in no coherent system, and sometimes with conflicting designations of substages. Further, these lettered substages denoting intervals of time are commonly interwoven if not confused with a numbered system that was formulated to identify events rather than intervals, as discussed below. As a result, researchers are left with an inconsistent and sometimes conflicting nomenclature originating in a diverse and scattered literature.

In light of the usefulness of isotope stages and lettered substages, but also the piecemeal origin and disarray of the substage nomenclature, we review the origins of Quaternary isotope chronological schemes and tabulate the earliest reports of the lettered isotope substages. We then present a scheme of lettered isotope substages consistent with the previous scattered designations that have appeared in the literature, with the hope that this scheme can avoid further contradictions and provide a single unified source for future researchers. This scheme is defined relative to the LR04 stack of marine benthic oxygen isotope records, a continuous record that largely represents changes in ice volume that are inherently global and thus useful for global correlation.

2. Evolving concepts of stages and events

2.1. Named continental stages and substages (before 1940)

The concept of stages as deposits representing intervals of time, which are formally known as "ages" (Salvador, 1994), in Pleistocene history (e.g., Cohen et al. 2013) derives from named stages, such as Wisconsin and Kansan (Geikie, 1894; Chamberlin 1895) (Table 1). Those stages were defined by climatically significant continental deposits, rather than by faunal zones, in the peculiarly Quaternary paradigm (Flint, 1947, p. 209) now known as "climatostratigraphy" (Mangerud et al., 1974; Harland, 1992; Gibbard, 2014). More recent North American stages had named substages, such as the Iowan, Tazewell, Cary, and Mankato substages of the Wisconsin (Leighton, 1933).

2.2. Numbered marine stages, and their substages (1952–1969)

The more recent concept of numbered and marine, rather than named and continental, climatostratigraphic stages arose with the work of Arrhenius (1952). In plotting the concentration of $CaCO_3$ in marine sediment cores, Arrhenius (1952) made correlations using stages and substages numbered in decimal style, with the uppermost and therefore most recent stage designated "1" and followed by "2', "3.1", 3.2", "4" and "5". Arrhenius (1952) recognized that his odd-numbered stages represented interglacial periods and his even-numbered stages represented glacial periods, and he thought it "probable" that his youngest four glacial stages corresponded to the Nebraskan, Kansan, Illinoian, and Wisconsin "Ice Ages" (Arrhenius 1952, p. 200). His Fig. 3.4.2 recognized 18 stages over the last 1.0 million years, which was then considered the entirety of the Pleistocene. Today, more stages are identified over both of those intervals (e.g., Lisiecki and Raymo, 2005), but the system of stages generated by Arrhenius (1952) provided a conceptual framework that was used when isotopic, rather than compositional, analysis of marine cores (e.g., Emiliani, 1955) began soon after his work. Within that system, his stages numbered with integers clearly referred to *intervals* of sediment or time (e.g., in his Fig. 3.4.2), but his only illustration showing substages numbered in decimal style (his Fig. 1.2.4) used lines pointing to peaks in his data, implying that these chronological features numbered in decimal style were viewed as events as much as intervals (Fig. 1A), a distinction that would become critical by the 1980s.

Emiliani (1955), in characterizing the variability of his oxygen isotope data from deep-sea cores, adopted the system of stages initiated by Arrhenius (1952). Emiliani (1955) recognized 14 numbered "core stages" in his Figs. 3 and 15, in analogy to and for correlation with continental glacial stages, as in his Table 15. Emiliani (1955) in some cases wrote about the "thickness" of stages (his p. 554) and elsewhere used time terms (e.g., "preceded by" on his p. 566 and "earlier" on his p. 557) to characterize stages. Emiliani's Fig. 1 clearly labelled stages with a time, rather than depth or thickness, axis. He thus made the transition from "stage" as a term for sediments deposited during an interval of time to "stage" as a term for an interval of time. The use of "stage" rather than "age" (Table 1) as a term for time in isotopic stratigraphy has persisted, with implications discussed in Section 5.2.

Emiliani (1955) designated the present and previous interglacials as MIS 1, 5, 7, 9, 11, etc., with MIS 3 as an interval that is no longer considered an interglacial (e.g., Sirocko et al., 2007). That usage has persisted to the present, despite its imperfection as an arithmetic series, and its persistence illustrates the extent to which the system of isotope stages is a matter of consistent communication, rather than of contemporary geological reasoning. Its persistence as a mathematically flawed but widely used chronological system is paralleled by the even more widespread persistence of numbers used to identify years before (BCE) or after (CE) a datum now acknowledged to have been misplaced by about five years (Teres, 1984; Maier, 1989). In both cases, the need for consistency of usage has triumphed over logic and purity of system.

Emiliani (1955) designated no marine substages, despite explicitly noting continentally-defined intervals such as the Allerød and Two Creeks that he called "substages". Emiliani (1961) followed his earlier publication (Emiliani, 1955) in recognizing 14 numbered stages in his Fig. 9, and in his Fig. 10 he subdivided Stage 5 into five un-labelled intervals of isotopic maxima and minima of lesser relative magnitude than those defining stages. Shackleton (1969) explicitly labelled those five intervals as “isotope sub-stages” with letters “a” to “e” in his Fig. 1, and he discussed “Substage 5e” extensively. Fig. 1 of Emiliani (1955) explicitly conceptualized stages as *intervals* of time with boundaries at changes in temperature, and Fig. 10 of Emiliani (1961) and Fig. 1 of Shackleton (1969) implicitly but clearly followed that model with substages as successive contiguous intervals of time (Fig. 1B), in contrast to later schemes.

From the 14 isotope stages first recognized by Emiliani (1955), Emiliani (1966) extended the system of isotope stages back to Stage 17 in his Fig. 6, and Shackleton and Opdyke (1973) extended it to Stage 22 in their Fig. 9. Van Donk (1976) extended the system back to MIS 42 in his Fig. 1, Ruddiman et al. (1989) extended the system of MIS stages to MIS 63 in their Fig. 7, and Raymo et al. (1989) extended it from MIS 63 to MIS 116 in their Fig. 6 (but see also Shackleton et al. 1990). Shackleton et al. (1995) extended the system back to the Miocene, and thus to give a total of 220 marine isotope stages, in their Fig. 7. These stages beyond MIS 5e were designated only with integers, and no substages were recognized, and thus neither letters nor decimal-style numbers were used. Shackleton et al. (1995) did, however, remark that “lettered substages” might eventually be useful in the early stages that they defined.

In the lineage from Arrhenius (1952) to Shackleton (1969) described above, a transition was made from the non-isotopic substages with decimal-like numbers of the former to the lettered isotopic substages of the latter. Shackleton (1969) cited Arrhenius (1952) but made no mention of the numbered substages in that paper, leaving the previous use of decimal-style numbers by Arrhenius seemingly forgotten, and thus leaving decimal-style numbers free for application to isotopic “events” recognized in marine cores in the 1980s.

2.3. Events (1984–1994)

Prell et al. (1986, p. 138) explicitly rejected the substage concept of Shackleton and Opdyke (1973) because stages and substages, as intervals, were argued to not provide the distinct control points needed to construct age models. Instead, Prell et al. (1986) used decimal-style numbers to label "events", which were much briefer intervals at "maxima, minima, or rapid changes" in the oxygen isotope record (Fig. 1C). The end of one event was commonly not the beginning of the next, so that intervals of time between successive events were left without designation. Numbers such as 2.0, 3.0, 4.0, etc., indicated boundaries, rather than intervals, and they marked the boundaries of the isotope stages of Emiliani (1955).

Despite its publication date, Prell et al. (1986) was the cited source of systems used in Imbrie et al. (1984) and Pisias et al. (1984). Imbrie et al. (1984) adopted a system of decimal-style numbered "events", with boundaries at 2.0, 3.0, 4.0, etc., like that of Prell et al. (1986). Pisias et al. (1984) used a similar series of decimal-style numbered "events" and cited Prell et al. (1986) as a source, but they moved further from the model of Emiliani (1955), Imbrie et al. (1984), and Prell et al. (1986) by using 1.0, 2.0, 3.0, etc. to label events that were intervals of non-zero duration (Fig. 1D), rather than to label boundaries as Prell et al. (1986) had done.

Martinson (1987) cited Pisias et al. (1984) as the source of their system of decimal-style numbered events. However, Fig. 18 of Martinson et al. (1987) suggests that each of that publication's events, whether at transitions or at peaks or troughs, had no significant duration in time (Fig. 1E), in contrast to the bracketed events of measurable duration shown by Prell et al. (1986). Martinson et al. (1987) joined Pisias et al. (1984) in taking some decimal-style designations to two places, as for example with Events 5.51 and 5.53 within Event 5.5 in Fig. 18 of Martinson et al. (1987). The series of publications from Prell et al. (1986) to Pisias et al. (1984) and Imbrie et al. (1984) to Martinson et al. (1987) thus presents an evolving number-based scheme of events, rather than contiguous intervals, different in intent and form from the lettered substages of Shackleton (1969).

Bassinot et al. (1994) continued this tradition by extending the system of numbered events back to MIS 22 in their Fig. 7, and they maintained that tradition's focus on isolated peaks, rather than on continuity of contiguous intervals, by not designating an Event 6.4 between their Events 6.3 and 6.5, and likewise by not designating an Event 17.2 between their Events 17.1 and 17.3. Bassinot et al. (1994) consistently referred to integer-numbered stages (e.g., "Stage 19"), decimal-style numbered events (e.g., "Isotopic Event 19.1"), and decimal-style numbered stage boundaries (e.g., "Isotope stage boundary 23.0"), completely consistent with the conceptual separation of lettered substages and decimal-style numbered events arising from the papers discussed above. However, later workers would not maintain that distinction in using the decimal-style numbers established by Bassinot et al. (1994).

2.4. Hybridization and modification (~1990 to present)

Despite the distinction between stages and events established in the 1980s, later workers have gone on to hybridize these schemes. For example, Plagnes et al. (2002), Wang et al. (2008), Kitaba et al. (2011), and Muhs et al. (2014) used decimal-style numbers to one place to identify substages, rather than events (Fig. 1F). Bühring et al. (2004) used decimal-style numbers to two places to identify substages and drew these numbers from those used to identify events by Imbrie et al. (1984) in some cases and by Martinson et al. (1987) in others. Poli et al. (2012) likewise used decimal-style numbers to two places to identify substages, but they drew the numbers from those used to identify events by Bassinot et al. (1994). In their text, Bühring et al. (2004) innovated further by using substage designations with two decimal-style dots, as in their substages 5.3.1 and 5.3.3. In a more complex hybrid, Jahns et al. (1998) combined decimal-style numbers and letters in identifying single substages when they referred to "δ^{18}O-substage 12.2h", and Desprat et al. (2007) combined lettered and numbered substages (e.g, 8.2, 9e, and 11.3) in one series in their Fig. 25.3.

Meanwhile, other workers challenged some of the original premises of earlier schemes.

For example, Melles et al. (2007) and Vaks et al. (2010) extended the use of numbers with Substage 6.1, and Melles et al. (2007) wrote of Substage 8.1, whereas none of the founding papers of the 1960s to 1990s discussed above had referred to an event or substage 2.1, 4.1, 6.1, or the like. That prior convention presumably prevailed because an even-numbered and therefore glacial stage was not expected to end with a warm (odd-numbered) phase prior to a typically abrupt termination.

2.5. Shackleton's valedictory perspective (2006) and beyond

Nicholas Shackleton (1937–2006) was the author of the first paper identifying lettered isotope substages (Shackleton, 1969) and a co-author of the papers establishing the systems of numbered events (Pisias et al., 1984; Imbrie et al., 1984; Prell et al., 1986; Martinson et al., 1987; Bassinot et al. 1994), and a co-author on many of the works cited in Section 3 of this paper. In his INQUA Presidential Address published as an "unfinished" paper in 2006, Shackleton reiterated the difference between, on the one hand, substages representing bounded intervals that collectively account for all of past time and, on the other hand, numbered events representing points in time between which some intervals of time are undesignated (Shackleton, 2006). He concluded that "the two systems are not interchangeable".

We concur that the two systems are not interchangeable, for two reasons. The first reason, a conceptual one, is the contradiction above between contiguous intervals and discrete events that was presented by Shackleton (2006) and that was implied in the explicit rejection of stages and substages by Prell et al. (1986). The second reason, a practical one, is that the assumption that the number "1" means "a", "2" means "b", etc., fails when one encounters an interval numbered "X.0" (as in Wang et al., 2009 and Kitaba et al., 2011) because zero has no analog among letters. Thus one cannot assume that "readers will know what we meant" when the nomenclature of numbered events is applied to time intervals. In fact, the example from Fig. 8 of Kitaba et al. (2011) is additionally instructive because that figure identifies two successive substages, 22.0 and 22.2, with no intervening 22.1, a designation compatible with the numbering of events but incompatible with a succession of stages.

One recent and well-expressed example of the two systems can be seen in Figs. 3 to 6 of Hernández-Almeida et al. (2012). These figures show the extent of MIS 20 to 30 in blue and white bands between which there are no gaps, consistent with the notion of stages presented by Emiliani (1955) and Shackleton and Opdyke (1973). The figures also show decimal-style numbered events in red bands that are not contiguous. Events 24.1 and 29.1 are intervals of short duration in the middles of MIS 24 and 29, respectively, and Event 30.1 is an event of short duration at the beginning of MIS 30. The decimal-style numbered events are thus consistent with the spirit of Pisias et al. (1984), Imbrie et al. (1984), Prell et al. (1986), and Martinson et al. (1987) in marking isolated points in time. However, any attempt to convert these decimal-style numbered events to substages would fail, because substages designated “1” or (more appropriately) “a” should be at the end, rather than middles or beginnings, of the sequence of substages in a stage.

3. Extension of lettered substages to time other than MIS 5, and resulting problems

In the last four decades, the system of lettered substages has been extended to time other than Shackleton’s (1969) MIS 5 substages (Table 2). However, that extension has been accomplished largely in an *ad-hoc* fashion wherein lettered substages were denoted, but not defined, in order to meet the needs of the subject matter of specific papers, some of which dealt with terrestrial rather than marine deposits (Table 2). In some papers, substage designations were used in figures but not mentioned in text, and in some cases substage designations were mentioned in text but not illustrated in figures (e.g., Ninkovich and Shackleton, 1975). In almost no cases were boundary lines between substages like those of Shackleton (1969) (Fig. 1B) drawn on isotope time-series plots. Our compilation in Table 2 shows that the first occurrences, and in some cases only occurrences, of use of these lettered substages outside MIS 5 are scattered across at least 19 papers. Despite this proliferation, some substages remain without explicit identification amidst substages that have been labelled (e.g., Substages 13b and 16b).

In the midst of this piecemeal extension of lettered substages, contradictions have developed (Fig. 2). Some examples, presented only to illustrate the hazards of this *ad-hoc* way of creating a chronology, include the following:

1) Lundberg and MacFarlane (2007) designated three substages of MIS 6 (6c, 6b and 6a), and they specifically defined MIS 6c as “the first cold period of MIS 6”. On the other hand, Sun and An (2005) discussed five substages of MIS 6 (6e, 6d, 6c, 6b and 6a), of which MIS 6e was the earliest of three MIS 6 cold substages in their Fig. 7. Meanwhile, Kawamura et al. (2007) designated five MIS 6 substages as MIS 6f, 6e, 6d, 6c and 6b, with MIS 6f as the earliest cold substage and no MIS 6a at all in their Figure 2, a usage later employed by Railsback et al. (2014).

2) Ninkovich and Shackleton (1975) designated the earliest substage of MIS 7 as MIS 7c, Bussell and Pillans (1997) made the same designation (citing the decimal-style numbered events of Imbrie et al. 1984 and Martinson et al. 1987 as their source), and Zazo (1999) similarly identified MIS 7c and 7a as the two highstands of MIS 7, whereas Tzedakis et al. (1997) designated the earliest substage of MIS 7 as MIS 7e, a usage subsequently followed by Schreve (2001), Robinson et al. (2002), Siddall et al. (2007, their Table 7.1), and Compton (2011).

3) Bassinot et al. (1994) identified as Isotopic Event 8.5 the peak that Tzedakis et al. (1997) designated as MIS 9a, a contradiction not only of substages but of stages.

4) Bussell and Pillans (1992), Bradley (1999, 2015), and Siddall et al. (2007) labelled the earliest peak in MIS 9 as MIS 9c, whereas Tzedakis et al. (1997) designated that peak as MIS 9e, and it was subsequently identified as MIS 9e on the Quaternary chronostratigraphical charts of Gibbard and Cohen (2008) and Cohen and Gibbard (2011) and in Fig. 25.3 of Desprat et al. (2007). On the other hand, Fig. 3 of Westaway (2011) presented a detailed series of substages from MIS 5a to MIS 15e in which all of MIS 9 was labelled only “9” without subdivision.

5) Prokopenko et al. (2001) and Schreve (2001) referred to MIS 11e, and Ashton (2010) similarly

referred to MIS 11d and MIS 11e, although Tzedakis et al. (1997) had defined MIS 11c as the earliest substage of MIS 11. On the other hand, de Abreu et al. (2005) referred to MIS 7e and 9e, evidently finding these lettered substages of use, in a paper focused on MIS 11 in which they found no reason to refer to any substages of MIS 11 at all. Fig. 3 of Westaway (2011) likewise presented a detailed series of substages from MIS 5a to MIS 15e in which all of MIS 11 was labelled only "11" without subdivision.

6) Tzedakis et al. (2012a,b) labelled the earliest substage of MIS 15 as MIS 15c, whereas it had been identified as MIS 15e by Khursevich et al. (2001) and Westaway (2011) and on the Quaternary chronostratigraphical charts of Gibbard and Cohen (2008) and Cohen and Gibbard (2011).

Meanwhile, attempts at numbered substages have fared no better. For example, Wang et al. (2008) identified as Substage 7.0 the same interval that Bühring et al. (2004) designated as MIS 6.6. Similarly, Vaks et al. (2010) identified the youngest substage of MIS 6 as MIS 6.1, whereas Ruddiman (2006) had identified it as MIS 6.2. All eight examples combine to illustrate the confusion that can arise when no single system exists to divide time series.

4. A proposed system of lettered substages

The long history of repeated attempts to label parts of Cenozoic time series at fine scale shows that this is a useful and desirable component of communication about Earth history. However, the piecemeal and *ad-hoc* approach to substages and its resultant contradictions (Fig. 2) imply that a systematic development of substage taxonomy and nomenclature would be more useful. We therefore propose the complete scheme of lettered substages shown in Fig. 3. Our goals in preparing this scheme have included the following:

1) Definition of substages relative to a marine isotope record, rather than a terrestrial one. This follows logically from the expression "*Marine* Isotope Stage", and it is consistent with the objective of identifying time intervals that are meaningful at global, rather than regional, scale.

Fig. 3 therefore shows three marine records, and its substages are defined relative to the LR04 stack of marine benthic oxygen isotope records of Lisiecki and Raymo (2005). However, Fig. 3 additionally includes four non-marine records that provide a basis for comparison with less complete non-marine records from which some substages may be missing. The seven records in Fig. 3 combine to provide depositional diversity (marine sediments, glacial ice, lacustrine silica and pollen, and loess) and geographic diversity (Northern and Southern Hemispheres, and Atlantic and Pacific). The records are also diverse in their applicability, in that the Lake Baikal silica record of Propkopenko et al. (2006) characterizes substages of interglacial stages clearly, whereas the Chinese loess record of Sun et al. (2006) conversely characterizes substages of glacial stages clearly. Nonetheless, using benthic foraminiferal isotope records to define our scheme means that it should substantially reflect global ice volume changes and therefore be applicable across both hemispheres.

2) A scheme as consistent as possible with previous designations of substages, so as to minimize conflict with the previous literature. This requires the following:

2a) Stages that end with a substage designated “a”, and earlier substages are designated with the sequence of letters of the Latin alphabet, consistent with the first lettered substages defined by Shackleton (1969). This system precludes the interposition of additional substages by later workers but avoids the confusion that would be inherent in a system with missing letters that were subsequently inserted piecemeal.

2b) Substages that have been defined by their apparent paleoenvironmental significance, and therefore by human inspection. One might argue for a scheme in which substages, and by necessity stages as well, were identified by a mathematical or statistical algorithm, seemingly independent of human judgment. Alternatively, one might argue for a theoretical approach in which substages and stages were defined according to Milanković insolation cycles. However, either approach would eliminate any continuity with the previous literature, because MIS 5 would become MIS 3, as discussed in Section 2.2, and MIS 5e would become

MIS 3e if not MIS 3c. With an algorithmic or theoretical approach, the earlier substages of MIS 18 would likely become substages of MIS 19, which would, with the elimination of present MIS 3 and 4, become MIS 17. Similarly, an algorithmic or theoretical approach would likely designate MIS 24 as a substage of one stage consisting of present Stages 23 to 25, all of which would, with the elimination of present MIS 3 and 4, become MIS 21 – and the result would be great confusion between previous and future publications.

2c) Substages that are consistent with designations by previous workers (Table 2) to the maximum extent possible.

3) Assignment of all intervals of time to stages and substages, in accord with Fig. 1 of Emiliani (1955) and in contrast to the schemes of Pisias et al. (1984) and Prell et al. (1986) for events.

4) Explicit divisions between, and thus definition of, each substage, as shown for the stages of Fig. 1 of Emiliani (1955) and the substages of Fig. 1 of Shackleton (1969) but rarely shown in subsequent publications.

5) No substages that are left unidentified (e.g., no “b”s left unused or merely implicit between “a”s and “c”s), in contrast to many designations of substages prior to MIS 5e.

Applying these goals has led us to the scheme of substages shown in Fig. 3. No substages are designated for MIS 1 (the Holocene), MIS 2, and MIS 4 for three reasons: they are all brief stages, they are stages for which substages have never been designated in marine records, and they are in the time interval in which numbered Greenland Stadials and Greenland Interstadials (Dansgaard et al., 1993; Eiriksson et al., 2000) are now widely applied in recognizing substage-scale periods (e.g., Schulz et al., 1997). For MIS 3, which is almost as long as MIS 1, 2 and 4 combined, the three substages are those recognized by Carey et al. (2005) in East Pacific Core V19-30 and by Wright et al. (2009) in the North Atlantic, and they are similar to those of Wu et al. (2004) in data from Tibetan ice. They are evident in LR04 and further supported by the Tenaghi Philippon record of Tzedakis et al. (2006). The five substages of MIS 5 shown are those of Shackleton (1969), which he defined relative to a generalized oxygen isotope record. The five substages of MIS 6, which were first designated by Sun and An (2005), are easily recognized in the LR04 record, and are further supported by the Chinese loess record of Sun et al. (2006) (Fig. 3). The five substages of MIS 7 and 9, which are easily recognized in LR04, are those designated by Tzedakis et al. (1997). The three substages of MIS 8 are clearly recognized in the LR04 record and further supported by the Lake Baikal and Tenaghi Philippon records of Prokopenko et al. (2006) and Tzedakis et al. (2006), respectively. The three substages of MIS 10 are easily recognized in LR04, are strongly supported by Antarctic ice and Tenaghi Philippon records in Fig. 3, and are in accord with the MIS 10a, 10b, and 10c discussed but not illustrated by Lundberg and McFarlane (2007). The substages of MIS 11 can be recognized in LR04 and are strongly supported by the Antarctic and Lake Baikal records. The three substages of MIS 12 are most readily recognized in the marine record of Hodell et al. (2008). The three stages of MIS 13 are readily evident in the marine records of Fig. 3 and additionally supported by the Antarctic ice, Tenaghi Philippon pollen, and Chinese loess records. The three substages of MIS 14 are readily evident in the marine record of Hodell et al. (2008). The five substages of MIS 15 first designated by Khursevich et al. (2001) can be recognized in the LR04 record and are also evident in the marine record of Hodell et al. (2008) and the Antarctic ice record of Jouzel et al. (2007). The three substages of MIS 16 first designated by Sun and An (2005) are recognizable in the marine records of Hodell et al. (2008) and Fig. 2 of Naafs et al. (2011), and they are further supported by the Antarctic ice record of Jouzel et al. (2007) and the Chinese loess record of Sun et al. (2006) (Fig. 3). The five stages of MIS 17 are evident in LR04 and supported by the Lake Baikal record of Prokopenko et al. (2006). The five substages of MIS 18 are evident in LR04 and the marine record of Hodell et al. (2008), and they are supported by the Lake Baikal record of Prokopenko et al. (2006). The three substages of MIS 19 were first designated by Tzedakis et al. (2012 a, b) and can be recognized in LR04. The four substages of MIS 20 are evident in the marine record of Hodell et al. (2008). The seven substages of MIS 21 are evident in the marine records of Hodell et al. (2008) and Fig. 2 of Naafs et al. (2011), and less clearly but arguably in

LR04. They also parallel the seven numbered substages recognized by Ferreti et al. (2010). MIS 22, 24, 26, and 27 are sufficiently brief and invariant that there is little justification for designating substages within them. On the other hand, the three substages of MIS 23 and five substages of MIS 25 can be recognized in LR04, and the latter are supported by the Lake Baikal record of Prokopenko et al. (2006).

We have extended this scheme back 1.0 million years, and thus to MIS 27, because marine isotope stages before that time are both sufficiently short and their oxygen isotope data are sufficiently uniform internally that substages seem unnecessary at the present state of knowledge. Furthermore, U-Th dating has made detailed chronologies possible over the last 550,000 years and thus has necessitated substages back to MIS 14, but the use of substages before MIS 14 will presumably be less extensive. The compilation of usage in the literature shown in Table 1 suggests little applicability of substages before MIS 20 at about 800 ka, further suggesting little need to define substages before 1.0 million years – although it is implicit that the scheme proposed herein could in the future be extended further backwards if found desirable.

As isotopic records are further refined in the future, workers may also find it useful to define shorter-term oscillations in the marine record and thus to subdivide the marine isotope substages. With regard to marine isotope records, one step in that direction was taken by Bauch and Erlenkeuser (2008), who within MIS 5e recognized one interval, MIS 5e-*ss*, where "*ss*" represented "*sensu stricto*". That interval may have been similar to the MIS 5e "plateau" noted by Shackleton et al. (2003), which falls within the limits of MIS 5e. However, neither designation was part of a larger system of contiguous intervals within MIS substages, and the current state of marine isotopic and other records may make any attempt at such refinement premature now. Outside the realm of marine isotope stages, but in parallel with their usage, Dansgaard et al. (1993) and Greenland Ice Core Project (GRIP) Members (1993) recognized subdivisions of MIS 5e that they designated "MIS 5e1 to 5e5" in the GRIP $\delta^{18}O$ record. For the marine isotope record, we recommend the same scheme for labelling the subdivisions of substages.

5. The diversification of names and applications of stages, and its implications

5.1. Diversification

In the mid-1980s, the "stages" of Arrhenius (1952), "core stages" of Emiliani (1955, 1966), and then "isotope stages" of Shackleton (1969) and Shackleton and Opdyke (1973) progressed to "^{18}O stages" and "δ^{18}O stages" (Kukla, 1977) and "oxygen isotope stages" (e.g., Prell et al., 1986) and "marine isotope stages" (e.g. Porter, 1987), and most thoroughly to "marine oxygen isotope stages" (Scott et al., 1983). This was a progression toward greater specificity, as is shown by Fig. 4. However, time-series of isotopic data from marine sediments are so dominated by oxygen isotope data that "marine isotope stage" and "marine oxygen isotope stage" are nearly synonymous (Fig. 4), leading to the frequent and familiar use of "Marine Isotope Stage" and thus "MIS".

The material to which the terminology of marine isotope stages has been applied has also evolved, in that stages that were defined in oxygen isotope data from marine sediments have been used to label intervals in time-series of very different parameters from very different materials in very different settings. Examples include "oxygen isotope stages" applied to time-series of ^{10}Be concentration data in Fig. 4 of Eisenhauer et al. (1994), "oxygen isotope stages" applied to time-series of pollen data in Fig. 5 of Seidenkrantz et al. (1996), "isotope stages" applied to time-series of data about ice-rafted debris in Fig. 3 of Forsström (2001), and "marine isotope stages" applied to time-series of δ^{18}O data from $CaCO_3$ of stalagmites in Fig. 1 of Wang et al. (2008) and to time-series of deuterium concentrations in the EPICA Dome C ice core in Antarctica in Fig. 4 of Hur et al. (2013). Even more strikingly, "MIS 5e1 to 5e5" were *defined* relative to an ice-core record, rather than a marine record (Greenland Ice Core Project (GRIP) Members, 1993, their Fig. 2).

5.2 Implications for chronostratigraphy

The blurring of distinctions in materials and settings discussed above can mask differences in timing that can result from different time lags of different proxies, from different latitudinal settings, and from locations in different ocean basins (Fig. 5). For example, a transition defining the end of a substage or stage may progress in time from a low-latitude marine sedimentary record to mid-latitude stalagmite records (each with different time lags imposed by different rates of groundwater movement) to a high-latitude pollen record or an alpine ice-core record. Even within one type of data, benthic foraminiferal $\delta^{18}O$ records, Skinner and Shackleton (2005) found a 4-kyr Atlantic lead over the Pacific for the last deglaciation, caused by a local or basin-restricted component of this signal. Hodell et al. (2013, their paragraph 50) have pointed out similar lags in marine $\delta^{18}O$ records. It follows that numbered Quaternary *stages* (packages of sediment characterized by data recovered from them) are less *ages* (intervals of time) than *facies* (packages of sediment that may be deposited at slightly different times in different places in response to moving sets of depositional conditions and/or locally anomalous conditions) (Table 1). Indeed, the International Stratigraphic Guide (Salvador, 1994, p. 10) would consider these isotopic stages as *zones* akin to the range zones and assemblage zones of biostratigraphy or to the polarity zones of magnetostratigraphy. If we were to start isotope chronostratigraphy anew, as Wright et al. (2009) aspired when they proposed the use of "marine isotope chron" and thus "MIC" as a time term, we would call these units "marine isotope zones" labelled "MIZ" – but the desirability of nomenclatural stability dictates continued use of the customary, if technically incorrect, "marine isotope stage".

Because of the possibility of time mismatches caused by differences in kinds of data and by contrasting hydrographic settings, some authors may have been wise when, for example, they chose to call the MIS-like numbered intervals "climatic stages" when applied to time-series of paleomagnetic data (Rafalli et al., 1996) and to time-series of δD and dust data (Delmonte et al., 2004) (Fig. 4). Even Cesare Emiliani himself referred to the isotopically-defined intervals as "climatic stages" (Gartner and Emiliani, 1976). His usage is a reminder that all numbered Quaternary stages, whether identified in marine isotopic records, spelean isotopic records, pollen records, etc., have potentially diachronous transitions controlled by individual responses to changing climate, and they are therefore "climatic stages" in the climatostratigraphic paradigm. Thus, to use the example in Fig. 5, our proposed scheme of lettered substages (Fig. 3) attempts to eliminate confusion in the literature between Substage *n*a and Substage *n*c, but no such scheme can eliminate the possibility that the transition from Substage *n*b to Substage *n*a occurred at slightly different times in different places and/or in different records.

6. Consideration of potential problems in application to other records

The widespread designation of marine isotope substages discussed in Sections 2 and 3 suggests that the concept of substages is applicable to many records, both marine and non-marine. One might question how applicable this concept can be to discontinuous records from which some substages are missing, but examination of the Tianmen Cave (Cai et al., 2010) and Kesang Cave (Cheng et al., 2012) spelean records demonstrates that substages can be applied in radiometrically dated records with missing intervals. The Tianmen Cave stalagmites from the Tibetan Plateau were deposited over only about 30,000 of the last 120,000 years, but U-series dates combined with changes in $\delta^{18}O$ allowed clear assignment of stalagmite intervals to Marine Isotope Substages 5a, 5c, and 5e (Cai et al., 2010). Similarly, the Kesang Cave stalagmites from northwestern China were deposited over only about 80,000 of the last 130,000 years, but U-series dates and variation in $\delta^{18}O$ allowed recognition of Marine Isotope Stages 1 and 3 and of Substages 5a, 5c, and 5e (Cheng et al., 2012). In this respect, it is fortunate that speleothems, the paleoclimate records whose sensitivity to climate change makes them most prone to hiatuses (Railsback et al., 2013), are the records most readily dated by radiometric methods.

One might also question whether antiphasing might cause confusion in recognition of substages, in that a cold substage in one hemisphere might be a warm substage in the other.

However, several considerations combine to suggest that antiphasing should not be a major concern. First, our use of a benthic oxygen isotope record to define substages means that the substages are largely a function of changes in global ice volume (Shackleton, 2000; Elderfield et al., 2012), which is inherently an interhemispherical signal changing at time scales considerably greater than the mixing time of the oceans (Broecker and Peng, 1982). Secondly, modeling of changing ice volume suggests that, although antiphasing may have been an issue prior to about 1 million years ago, it has not been significant over the last million years (Raymo et al., 2006), although it is acknowledged that the harmonics of precession are significant features of some North Atlantic benthic oxygen isotope records (Ferretti et al, 2010), raising issues of potential antiphasing. Thirdly, the magnitude in offsets in Dansgaard–Oeschger events between northern and southern polar regions of 200 to 400 years (Hinnov et al., 2002) and in the bipolar see-saw with its offset of 1500 to 3000 years (Blunier and Brook, 2001) is sufficient to cause the sort of lags discussed in Section 5 but not sufficient to cause antiphasing of substages, given that our scheme of 94 substages across 1.0 million years gives an average duration for substages of more than 10 thousand years.

The arguments in the preceding paragraph apply mainly to benthic marine records and to records from high-latitude accumulations of ice. On the other hand, mid-latitude continental records and planktonic marine records may be more subject to antiphasing that would complicate application of substages. In the middle latitudes, fluctuations of continental climate are commonly linked to monsoonal variations, and increases in northern or southern hemisphere insolation can shift the Inter-Tropical Convergence Zone to the north or south and lead to more extensive monsoonal rainfall in the northern or southern hemispheres, respectively (e.g., Janicot, 2009). For example, Partridge et al. (1997) found an antiphase relationship in the North African and South African monsoons at orbital (precession) time scales. These longer-term antiphase relationships among various individual continental records may further demonstrate the importance of defining global substages relative to stacked marine benthic records.

7. Summary

Careful examination of the literature reveals that later Cenozoic time has been identified by two alphanumeric systems arising from the division of deep-sea sediment sequences, one identifying contiguous intervals by the use of numbered stages divided into lettered substages (Fig. 1B), and the other identifying non-contiguous events by the use of decimal-style numbers (Fig. 1C, 1D, and 1E). However, because the lettering of substages other than those of MIS 5 has never been formally defined, many conflicting designations and systems have been used for substages over the last twenty years (e.g., Fig. 2). We therefore propose one complete scheme (Fig. 3), with no internal contradictions and as compatible as possible with previous usage, for use henceforth in identifying substages in time-series of isotopic, as well as other, data (Fig. 4). This scheme, defined relative to the LR04 stack of marine benthic oxygen isotope records, extends designation of substages back to MIS 28, and thus back in time 1.0 million years.

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Table 1. Geochronologic intervals and their stratigraphic equivalents, with examples

Geochronologic (time) interval[1]	Chronostratigraphic (time-rock) interval[1]	Global chrono-stratigraphic example[2]	Climato-stratigraphic regional continental example[2]	Climato-stratigraphic marine isotopic example[2]
Period	System	Quaternary		
Epoch	Series	Pleistocene		
Age	Stage	Calabrian[3]	Wisconsin	MIS 7
Subage	Substage		Mankato	MIS 7b

[1] For the significance of this distinction, see Fig. 5 and Section 5.2, and more generally Salvador (1994).

[2] Note that these examples are not time-equivalents (e.g., Wisconsin is not Calabrian, and Mankato is not 7b).

[3] Cita et al. (2012).

Table 2. First designations of lettered substages

Substage	Earliest known use[1]	MIS literature cited	Record[2]
2a to 2h	Yelovicheva, 2006[3]	None	Non-marine sediments
3a and 3b	Wright et al. 1995	None	Marine $CaCO_3$
3c	Wu et al., 2004	None	$\delta^{18}O$ of Tibetan ice
3d and 3e	Yelovicheva, 2006	None	Non-marine sediments
4a to 4c	Yelovicheva, 2006	None	Non-marine sediments
5a to 5e	Shackleton, 1969	Emiliani (1961)	Marine $\delta^{18}O$
6a to 6e	Sun and An, 2005	None	Loess
6f	Kawamura et al. 2007	Tzedakis et al. 2004	Dome Fuji $\delta^{18}O$
7a, 7b, 7c	Ninkovich and Shackleton, 1977	Emiliani 1955, 1966; Shackleton 1969	Marine $\delta^{18}O$
7d	Prokopenko et al., 2001;	Imbrie et al. 1984	Lacustrine silica
	Khursevich et al., 2001	None	Lacustrine silica
	Forsström, 2001	None	Vostok δD
7e	Tzedakis et al., 1997	Imbrie et al. (1984); Prell et al. (1986); Martinson et al. (1987)	Marine $\delta^{18}O$
8a to 8c	None found	–	–
9a, 9b, 9c	Bussell and Pillans, 1992	Imbrie et al. 1984	Marine $\delta^{18}O$
9d	Prokopenko et al., 2001;	Imbrie et al. 1984	Lacustrine silica
	Khursevich et al., 2001	None	Lacustrine silica
9e	Tzedakis et al., 1997	Imbrie et al. (1984); Prell et al. (1986); Martinson et al. (1987)	Marine $\delta^{18}O$

10a, 10b, 10c	Lundberg and MacFarlane, 2007	None	Cave deposits
11a and 11c	Tzedakis et al., 1997, 2001	Imbrie et al. (1984);	Marine $\delta^{18}O$
		Prell et al. (1986);	
		Martinson et al. (1987)	
11b	Ashton et al., 2008[4]	Tzedakis et al. 2001;	Marine $\delta^{18}O$
		Prokopenko et al. 2001	
11d	Ashton, 2010[4]		
11e	Prokopenko et al., 2001	Imbrie et al. 1984	Lacustrine silica
12a, 12c, 12e	Sun and An, 2005	None	Loess
12b	Voelker et al., 2010	None	Marine $\delta^{18}O$
13a	Westaway, 2010	None	*Bithynia* ala/ser[5]
13c	Voelker et al. 2010	None	Marine $\delta^{18}O$
13b, 13d, 13e	None found	–	–
14a, 14b, 14c	None found	–	–
15a, 15b, 15c, 15d, 15e	Khursevich et al., 2001	None	Lacustrine silica
16a, 16c	Sun and An, 2005	None	
16b, 16d	None found	–	–
17a, 17b, 17c, 17d, 17e	None found	–	–
18a, 18b, 18c	None found	–	–
19a, 19b, 19d, 19e	None found	–	–
19c	Tzedakis et al.. 2012a;	None	Marine $\delta^{18}O$
	Tzedakis et al., 2012b	None	EPICA C δD
20a to 27e	None found	–	–

[1] This list shows the earliest use reported in searches of Web of Science, with earlier additions from the authors' knowledge.

[2] The record used to define the substage, which may not have been the kind of record studied.

[3] Yelovicheva (2006) explicitly labelled her eight substages as “MIS”. Murari et al. (2014) identified five monsoonal Himalayan-Tibetan stages (MOHITS) from 2A to 2E correlative with MIS 2, and Dortch et al. (2013) identified six semi-arid western Himalayan-Tibetan stages (SWHTS) from 2A to 2F correlative with MIS 2.

[4] Jahns et al. (1998) referred to “Pollen subzones” 11b and 11d in “oxygen isotope stage 11”, but they did not explicitly refer to substages designated 11b and 11d.

[5] Ratio of the amino acids alanine and serine in opercula of the freshwater gastropod *Bithynia*.

Fig. 1. Six different published styles of dividing Pleistocene time series, with the middle four from founding papers in the field of marine isotope stratigraphy discussed in Sections 2.2 and 2.3. The curve shown, and all of the letters and numbers, are arbitrary creations to illustrate the various schemes: “6” and “8” only suggest even numbers assigned to glacial periods; “7” only suggests odd numbers assigned to interglacials; etc. Dashed lines are boundaries between intervals; brackets identify short intervals; solid lines point to events of very short duration.

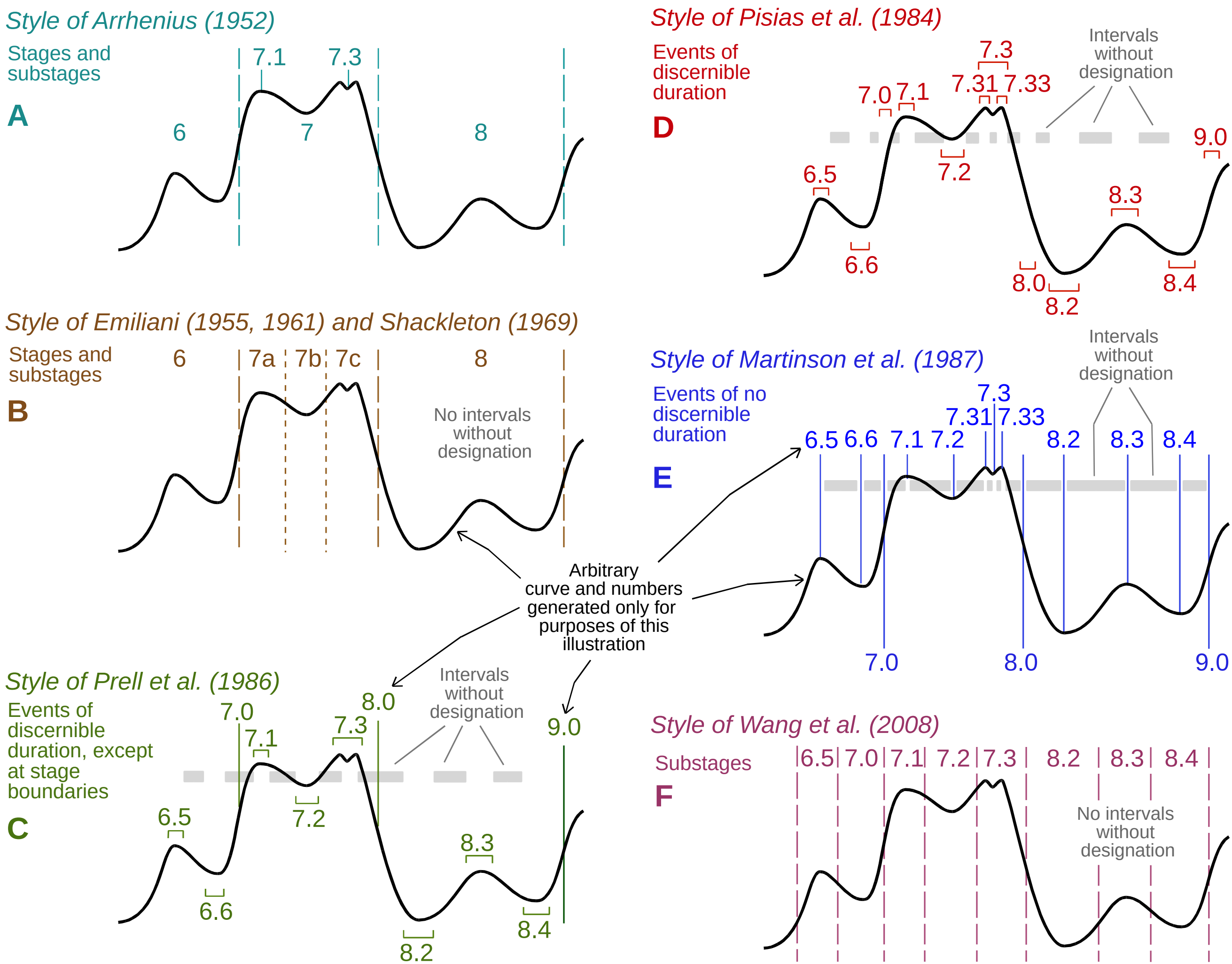
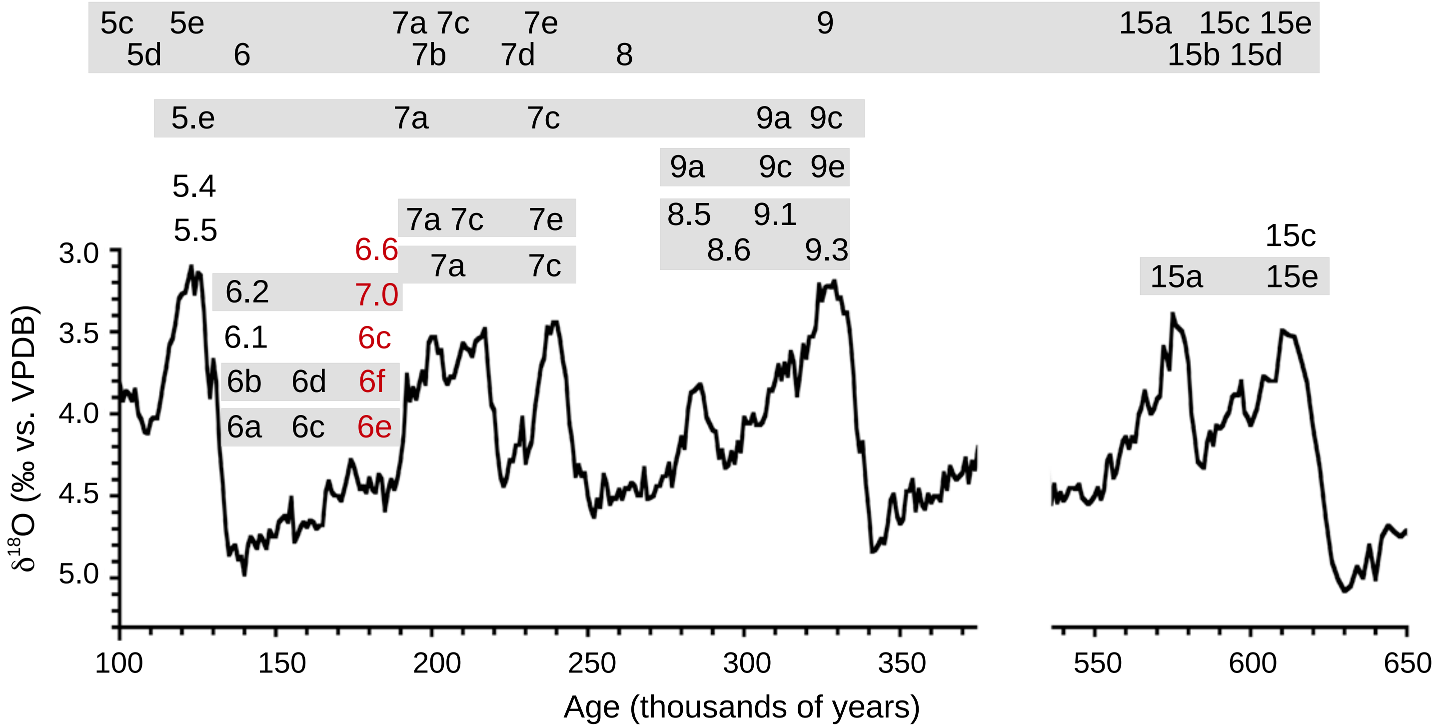
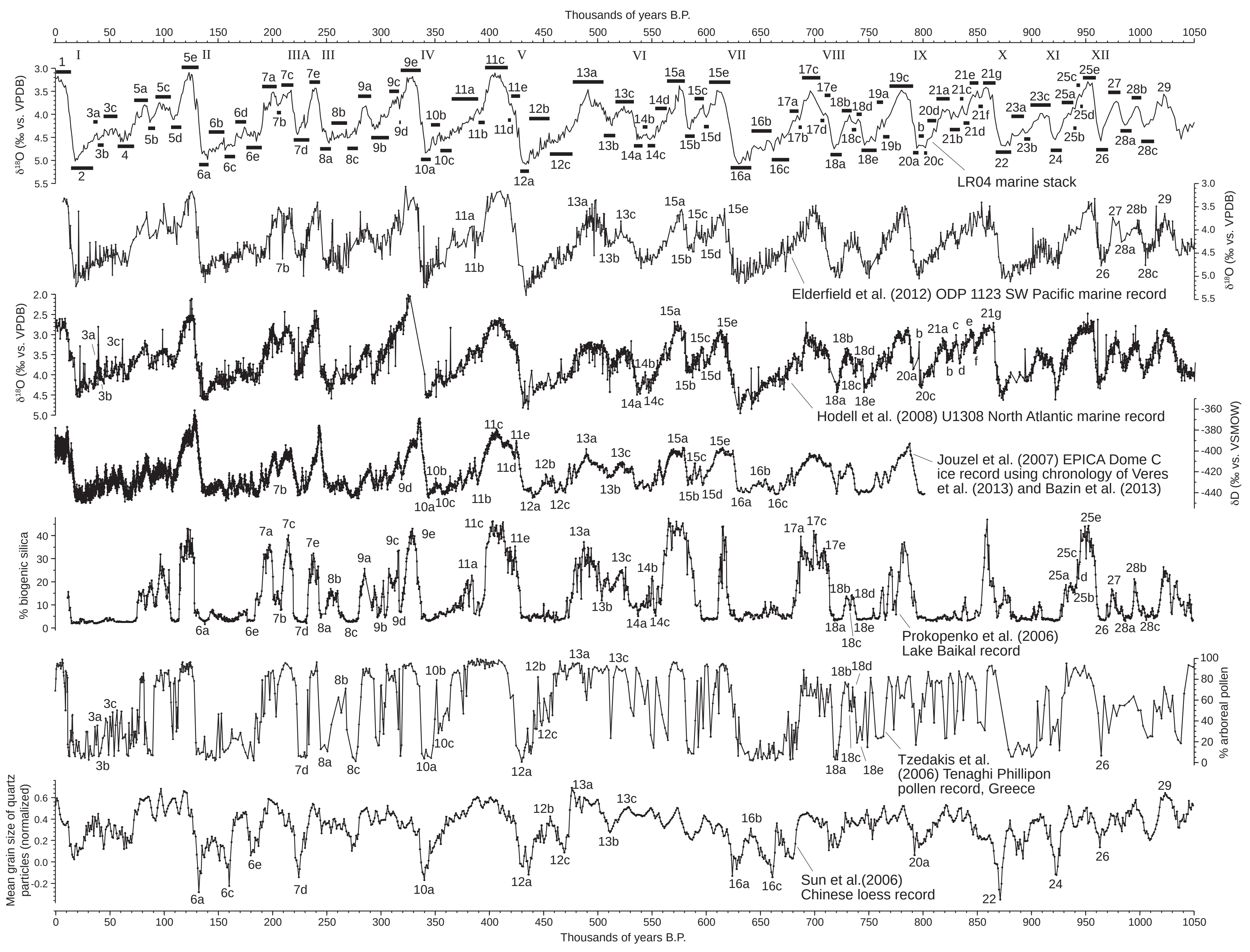

Style of Arrhenius (1952)
Stages and substages
A
7.1
7.3
6
7
8
Style of Emiliani (1955, 1961) and Shackleton (1969)
Stages and substages
B
6
7a
7b
7c
8
No intervals without designation
Style of Prell et al. (1986)
Events of discernible duration, except at stage boundaries
C
7.0
7.1
7.3
8.0
Intervals without designation
9.0
6.5
7.2
8.3
6.6
8.4
8.2
Arbitrary curve and numbers generated only for purposes of this illustration
Style of Pisias et al. (1984)
Events of discernible duration
D
7.3
Intervals without designation
7.0
7.1
7.31
7.33
9.0
7.2
6.5
8.3
6.6
8.0
8.4
8.2
Style of Martinson et al. (1987)
Events of no discernible duration
E
Intervals without designation
7.3
7.31
7.33
6.5
6.6
7.1
7.2
8.2
8.3
8.4
7.0
8.0
9.0
Style of Wang et al. (2008)
Substages
F
6.5
7.0
7.1
7.2
7.3
8.2
8.3
8.4
No intervals without designation

Fig. 2. Some examples of the contradictory designations of isotope substages used in the published literature from 1997 to 2015, as discussed in Section 3. Each gray box indicates assignments from one system of one publication. Red highlights the earliest substage of MIS 6, for which five different designations have been used in the literature.



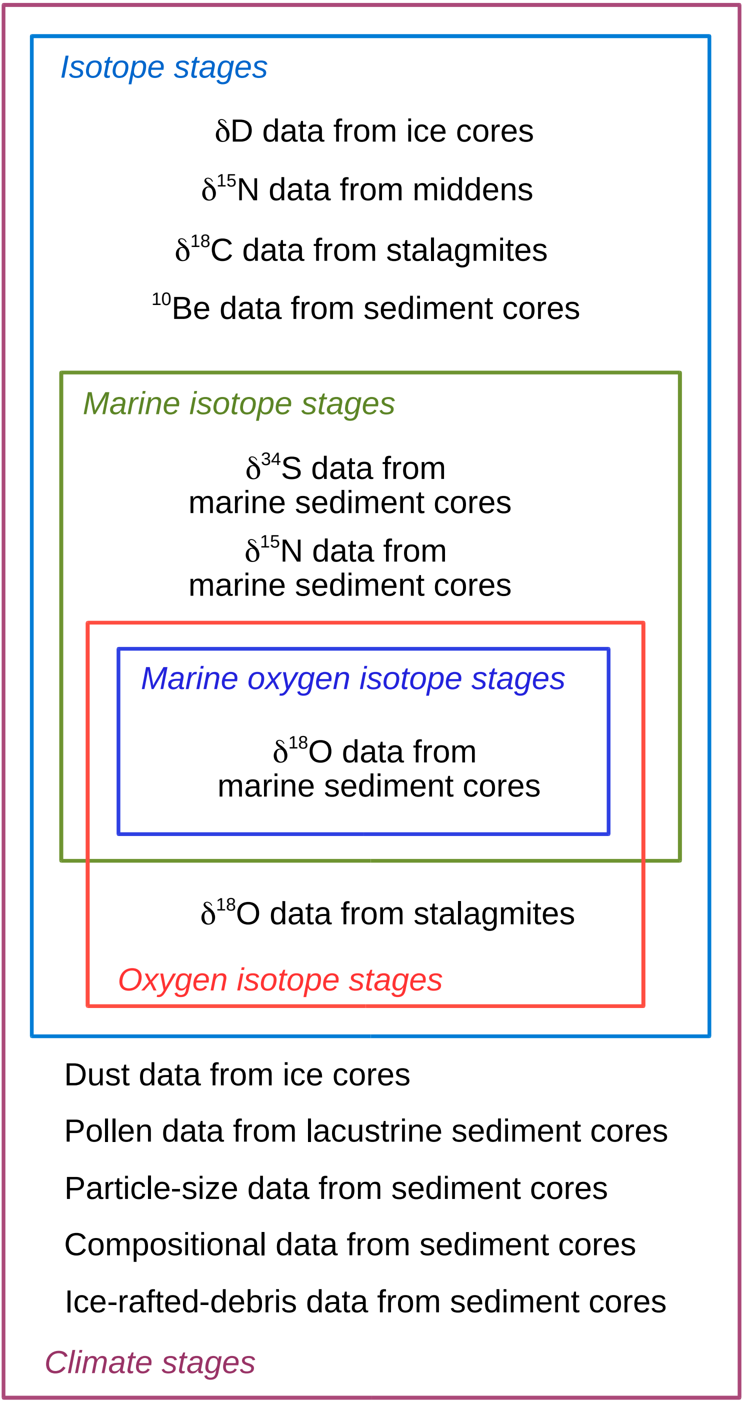
5c 5e 7a 7c 7e 9 15a 15c 15e
5d 6 7b 7d 8 15b 15d
5.e 7a 7c 9a 9c
9a 9c 9e
5.4
5.5
7a 7c 7e
8.5 9.1
8.6 9.3
7a 7c
6.6
7.0
6.2
6.1
6c
6b 6d 6f
6a 6c 6e
15c
15a 15e
3.0
3.5
4.0
4.5
5.0
δ18O (‰ vs. VPDB)
100 150 200 250 300 350 550 600 650
Age (thousands of years)

Fig. 3. Proposed scheme of marine isotope substages for the last 1.0 million years, defined relative to the LR04 stack of marine benthic foraminiferal $\delta^{18}O$ data of Lisiecki and Raymo (2005). Horizontal bars indicate the length of each substage. Many substages come from the sources listed in Table 1. However, many papers only labelled a peak or trough on a time-series diagram, with no indication of boundaries, and some papers only named the substage(s) in the text with no illustrative time series. The stages are taken from Shackleton and Opdyke (1973), Ruddiman et al. (1989), and Lisiecki and Raymo (2005). Roman numerals indicate terminations (Broecker and van Donk, 1970) or transitions (Jouzel et al., 2007) from glacial to interglacial stages, with Termination IIIA from Cheng et al. (2009). Six other time-series of data are shown to illustrate the relevance of the substages in those data. Criteria used in constructing this scheme are discussed in Section 4.



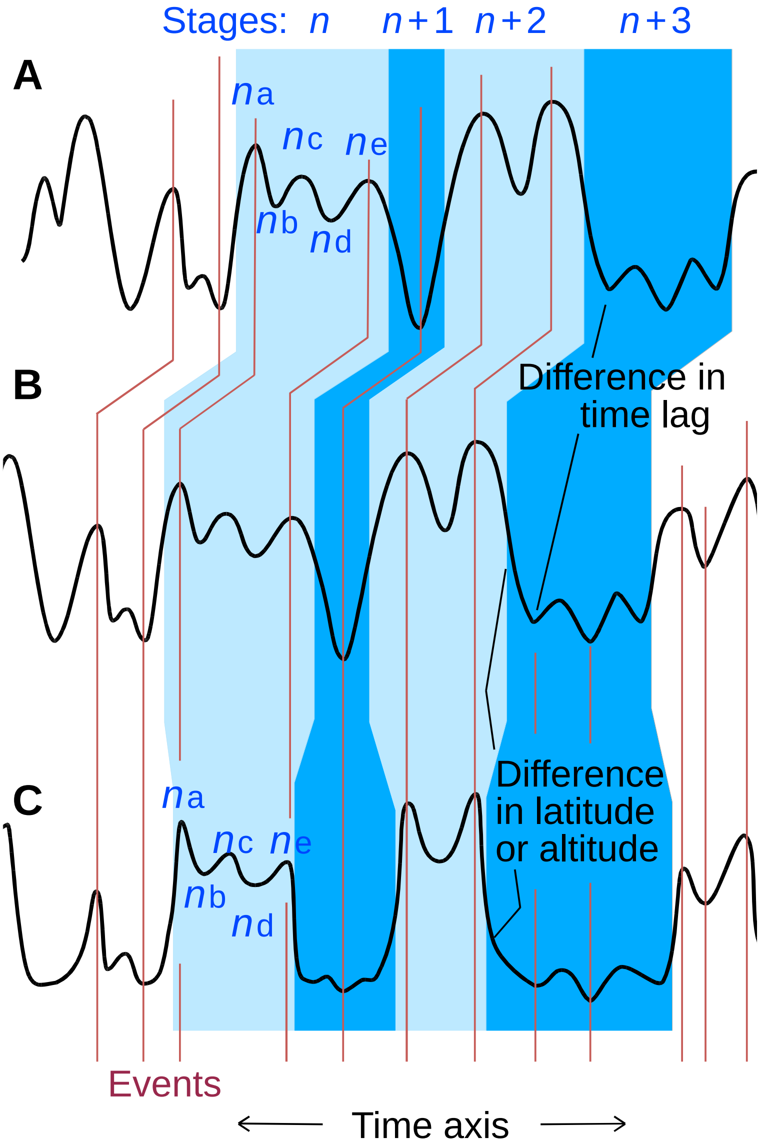
Thousands of years B.P.
LR04 marine stack
Elderfield et al. (2012) ODP 1123 SW Pacific marine record
Hodell et al. (2008) U1308 North Atlantic marine record
Jouzel et al. (2007) EPICA Dome C ice record using chronology of Veres et al. (2013) and Bazin et al. (2013)
Prokopenko et al. (2006) Lake Baikal record
Tzedakis et al. (2006) Tenaghi Phillipon pollen record, Greece
Sun et al.(2006) Chinese loess record
δ18O (‰ vs. VPDB)
δD (‰ vs. VSMOW)
% biogenic silica
% arboreal pollen
Mean grain size of quartz particles (normalized)
I
II
IIIA
III
IV
V
VI
VII
VIII
IX
X
XI
XII

Fig. 4. Euler diagram showing different kinds of time-series data and the kinds of stages that would be identified from them, as discussed in Section 5.1.



Isotope stages
δD data from ice cores
δ15N data from middens
δ18C data from stalagmites
10Be data from sediment cores
Marine isotope stages
δ34S data from marine sediment cores
δ15N data from marine sediment cores
Marine oxygen isotope stages
δ18O data from marine sediment cores
δ18O data from stalagmites
Oxygen isotope stages
Dust data from ice cores
Pollen data from lacustrine sediment cores
Particle-size data from sediment cores
Compositional data from sediment cores
Ice-rafted-debris data from sediment cores
Climate stages

Fig. 5. Three hypothetical sets of time series data illustrating chronological errors possible in identifying stages (blue) or events (red) from time-series data of different kinds, as discussed in Section 5.2. A and B combine to illustrate how differential time lags can cause faulty correlations in time of both stages and events; B and C combine to illustrate how difference in latitude or altitude can cause faulty correlations in time of stage boundaries. Comparison of B and C also illustrates why the dating of terminations may be more disputed than the dating of maxima or minima in some isotopic curves, supporting the preference of Prell et al. (1986) for use of events, rather than stages, for correlation to absolute time scales. The figure illustrates some aspects of the argument by Gibbard (2014) that "isotope stratigraphy is not strictly a chronostratigraphy".


Stages: n
n+1
n+2
n+3
A
na
nc
ne
nb
nd
B
Difference in time lag
C
na
nc
ne
nb
nd
Difference in latitude or altitude
Events
Time axis