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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.

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

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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, 2013). 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 labeled 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-labeled intervals of isotopic maxima and minima of lesser relative magnitude than those defining stages. Shackleton (1969) explicitly labeled 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, 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

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

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

[a] For the significance of this distinction, see Fig. 5 and Section 5.2, and more generally Salvador (1994).
[b] Note that these examples are not time-equivalents (e.g., Wisconsin is not Calabrian, and Mankato is not 7b).
[c] Cita et al. (2012).