

Marine isotope stages and substages

The study of deep-sea cores, and specifically the study of oxygen isotope ratios in foraminifera in those cores, has revealed a consistent pattern representing changes in the ocean-atmosphere system through time. Cesar Emiliani, who published the first report of such isotopic data in 1955, designated the major swings in his data as numbered stages, which are now commonly known as "Marine Isotope Stages". Nicholas Shackleton, a prominent scholar of the history of the oceans and climate, explicitly subdivided Emiliani's Stage 5 into lettered substages in a 1969 paper. Thus Quaternary time came to be divided into marine isotope stages and substages.

As time passed, other researchers followed Shackleton's lead, if less explicitly, by

designating other peaks and troughs in the marine isotopic time-series as substages. However, this was done with little attention to consistency, and eventually any one interval of the record had been assigned to as many as five different substages in different papers. In an effort to provide one consistent system, Railsback et al. (2015a) generated the scheme of marine isotope substages shown below.

The plot below is derived from Figure 3 of Railsback et al. (2015a), which extends back to MIS 28c at 1.0 mya. The oxygen isotope data are the LR04 stack of Lisiecki and Raymo (2005). The Mid-Brunhes Shift is from Berger and Wefer (2003), and the Early Brunhes Shift is from Railsback et al. (2015b).

Berger, W.H., Wefer, G., 2003. On the Dynamics of the Ice Ages: Stage-11 Paradox, Mid-Brunhes Climate Shift, and 100-ky Cycle. In: A.W. Droxler, R.Z. Poore and L.H. Burckle (eds.) *Earth's Climate and Orbital Eccentricity: The Marine Isotope Stage 11 Question*. AGU Geophysical Monograph 137, 41-59.

Emiliani, C., 1955. Pleistocene temperatures. *Journal of Geology* 63, 538-578.

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

Railsback, L.B., Gibbard, P.L., Head, M.J., Voarintsoa, N.R.G., and Toucanne, S., 2015. An optimized scheme of lettered marine isotope substages for the last 1.0 million years, and the climatostratigraphic nature of isotope stages and substages. *Quaternary Science Reviews* 111, 94-106.

Railsback, L.B., Brook, G.A., Ellwood, B.B., Liang, F., Cheng, H., Edwards, R.L., in prep. A record of wet glacial stages and dry interglacial stages over the last 560 kyr from a massive stalagmite in Carlsbad Cavern, New Mexico, USA.

Shackleton, N.J., 1969. The last interglacial in the marine and terrestrial record. *Proceedings of the Royal Society of London, B*. 174, 135-154.

