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The stratigraphy and nomenclature of millennial-scale climate change

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Summary

For the last glacial/interglacial cycle (last 115 ka) stratigraphy for abrupt or millennial-scale climate events is now following mostly the INTIMATE nomenclature of Greenland stadial/ interstadial cycles. The new IntCal13 calibration curve makes an essential step forward in the calibrating ^{14}C ages from Marine Isotope Stage (MIS) 3 and thus aligning records from different climate archives.

Keywords: Greenland interstadials, Greenland stadials, Heinrich events, Antarctic Isotope Maximum, IntCal13

With the records of the two ice cores, drilled at Greenland's summit (GRIP, GISP2) in the late 1980's, the world of the stratigraphy of the last glacial/ interglacial cycle (MIS 5d _ 1) changed forever. The Summit records confirmed the stadial/ interstadial cycles previously hinted at in the lower resolution ice core records of Renland and Camp Century, making the climate of MIS 3 much more unstable than previously indicated by the SPECMAP $\delta^{18}O$ record (Martinson *et al*., 1987). The Summit ice core records revealed 24 stadial/ interstadial cycles (Dansgaard *et al.,* 1993) that with the NGRIP ice core record were subsequently extended to 25. To distinguish the ice core stadials/ interstadials from those previously observed in terrestrial records they are referred to as Greenland stadials (GS)/ Greenland interstadials (GI) following the nomenclature of the INTIMATE group (Lowe *et al*., 2001; Blockley *et al*., 2012; Fig. 1). Each GI started with a rapid warming that is called Dansgaard-Oeschger event. Some GIs lasted longer than others and are correlated with interstadials long known from terrestrial records such as the Denekamp (GI 8), Hengelo (GI 12), Oerel (GI 14), and Glinde (GI 16) interstadials (Rousseau *et al*., 2006).

At the same time as the Greenland ice core records revealed the glacial climate instability, distinct layers consisting dominantly of lithic ice-rafted debris (IRD) were found in deep-sea cores from the North Atlantic's IRD belt, the Heinrich layers (Bond *et al*., 1992). With the evidence of abrupt climate changes found in the ice and marine cores the aim of particularly the paleoceanographic community was studying high sedimentation rate cores that would allow resolving GS/ GI cycles in the marine realm. Major progress was made and GS/ GI cycles were found in globally distributed records (Voelker & Workshop participants, 2002). An increased number of ice-rafting events was also identified in MIS 5. Establishing reliable age models, however, and correlation between the different climate archives still remained a problem, especially for ages older than 20 ka. In addition, evidence emerged that ice-rafting events such as those causing the Heinrich layers had a major impact on the scale of the surface ocean's reservoir age with reservoir ages exceeding 1000 years (Waelbroeck *et al.*, 2001; Sarnthein *et al.*, 2007). To circumvent some of these problems, marine records were tuned to Greenland ice core $\delta^{18}O$ records assuming contemporary changes in the ocean (on land) and on Greenland. Tuning does, however, not allow fully exploring the mechanisms behind the abrupt GS/ GI climate instabilities as leads and lags between the climate archives could not be studied. Tuning is also still controversial for records outside of the North Atlantic realm such as from China, the North Pacific or the Indian Ocean because the causal links between the GS/ GI cycles recorded in these regions and in Greenland have not fully been proven, yet. In

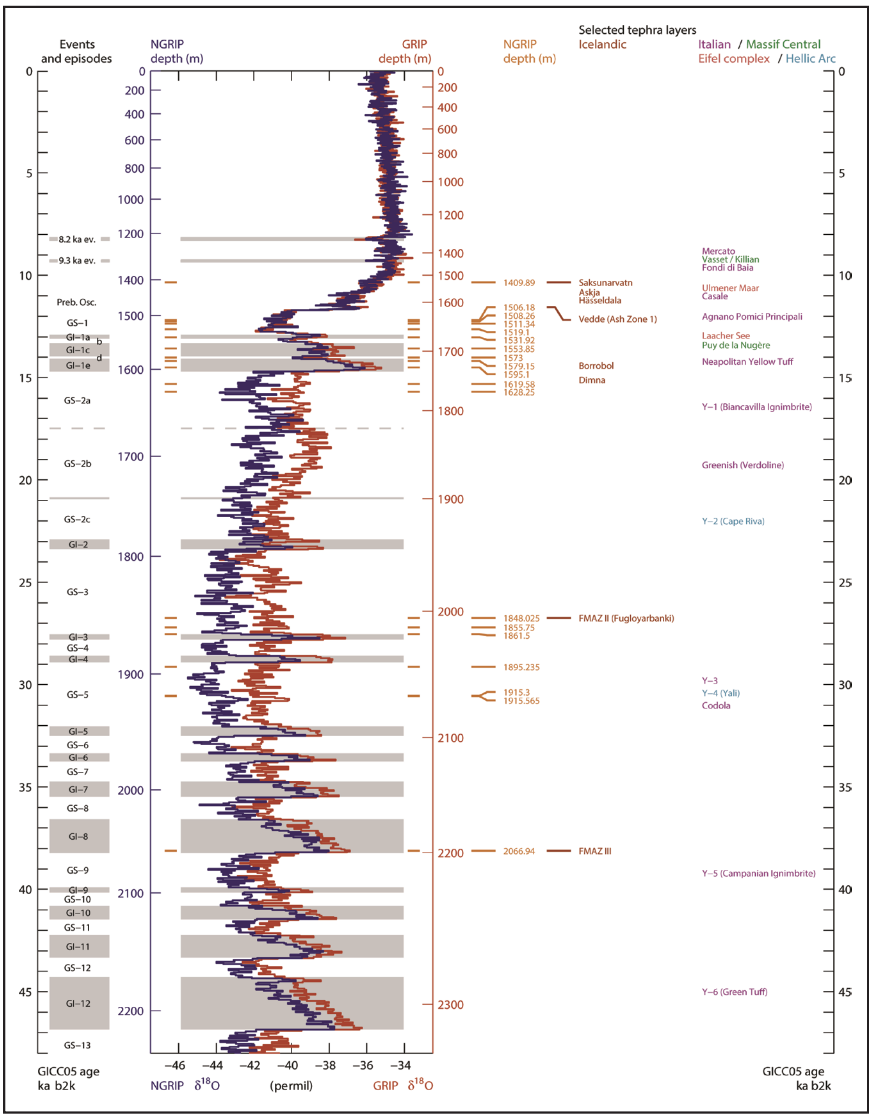

Fig. 1 – INTIMATE stratigraphy of Greenland stadial (GS)/ interstadial (GI) cycles for the last 48 kyr b2k (before 2000 AD) based on the Greeland ice core records and GICC05 ice core chronology and relevant tephra layers in Europe that can help in independently correlating marine and terrestrial sequences. Figure from Blockley *et al.* (2012).

the North Atlantic region, tuning assumptions could be confirmed for some records based on the occurrence of Icelandic tephra layers found in the ice and marine cores (Austin *et al.*, 2004, 2012). Distribution areas of Icelandic or Mediterranean tephras overlapping in central European areas, furthermore, allow synchronizing records from Greenland to southern Europe (Blockley *et al.*, 2012; Davies *et al.*, 2012; Fig. 1).

For a global synchronization, the Laschamp magnetic field intensity minimum and the associated peak in cosmogenic isotopes found in the ice cores during GI 10 provide the best control point (Mazaud *et al*., 2002; Muscheler *et al*., 2005). Linking southern hemisphere climate responses to the Greenland-type climate oscillations became possible through the synchronization of Greenland and Antarctic ice cores using their respective atmospheric methane concentration records (Blunier *et al*., 1998). The higher accumulation rates at the EDML ice core site later on allowed identifying that each GS had an Antarctic counterpart, called an Antarctic Isotope Maximum (AIM; EPICA Community Members, 2006; Fig. 2). Marine records from the southern hemisphere often show an Antarctic-type pattern of climate change. However, in specific regions of the world ocean, such as the deeper Portuguese margin, interhemispheric linkages can be studied because here the surface water record follows the GS/ GI cycles and the deep-water record reveals the AIM (Shackleton *et al*., 2000).

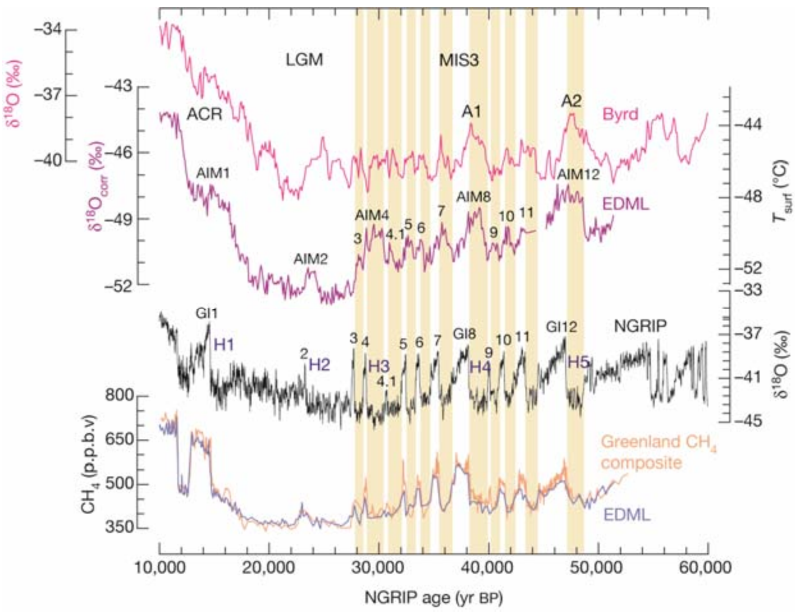

Fig. 2 – Correlation of Greenland and Antarctic ice core records showing the temporal relationship between Greenland stadial/ interstadial (GI) cycles and Antarctic Isotope Maxima (AIM). Byrd, EDML and NGRIP denote the respective ice core. ACR: Antarctic cold reversal; H1-H5: Heinrich event 1 to 5, respectively. LGM: Last Glacial Maximum; MIS3: Marine Isotope Stage 3. Figure slightly modified from EPICA Community Members (2006).

While consensus generally exists in identifying the GS/ GI or AIM in marine or terrestrial records, work on timing and thus duration and cyclicity of events still continues. For the Greenland ice cores annual layer counted chronologies were established for GISP2 (with 1950 AD = BP as reference age) and NGRIP (GICC05 chronology with 2000 AD = b2k as reference age). The GICC05 chronology that is now applied to many of the Greenland ice core records better incorporates accumulation rate changes during warm and cold stages than the GISP2 chronology leading to some age offsets between the two. Independent chronologies for the GI/ GS cycles arose from speleothem records (*e.g*., Wang *et al*., 2001; Spoetl & Mangini, 2002; Fleitmann *et al*., 2009) whose U/Th-age based chronologies mostly agree with the GICC05 chronology. For most marine and terrestrial sites, however, the only way to date the sediments is by radiocarbon (^{14}C). In previous years, calibration data for ^{14}C ages from MIS 2 and 3 was based on marine records for which the issue of potentially changing reservoir ages still remained. What was urgently needed was terrestrial calibration data beyond the range of the tree ring chronology that had at least partially an independent chronology. This was finally accomplished with the varve chronology dated Lake Suigetsu record (Bronk Ramsey *et al*., 2012) that will be incorporated into the new IntCal13 calibration data [Radiocarbon volume 55(2), *in* press].

Besides the absolute timing, the nomenclature for the abrupt climate change events during the last glacial/ interglacial cycle is not fully established, yet. Heinrich layers as initially described can only be found within the North Atlantic's IRD belt. Contemporary events were found north and south of the belt and in the western Mediterranean Sea and many authors referred to them as Heinrich events. Sanchez-Goñi & Harrison (2010) later on introduced the terminology of a Heinrich stadial (a GS associated with a Heinrich event) that includes a distinction between the duration of the surface ocean cooling related to a Heinrich event and the deposition of the IRD itself because outside of the IRD belt IRD deposition can be limited to a shorter interval than the cooling. The timing of a Heinrich layer/event within a GS is an outstanding issue. In the INTIMATE nomenclature (Blockley *et al*., 2012; Fig. 1) Heinrich layers/ events do not exist because their counterpart cannot directly be identified in the ice core records. Beyond Heinrich event 6 in MIS 4 no clear nomenclature exists for ice-rafting events in MIS 5. The best compilation of ice-rafting events and their timing in relation to the Greenland ice core records for the last 115 ka was done by Rousseau *et al*. (2006) though their GS/ GI identification should be adjusted to the INTIMATE nomenclature.

So while progress has and is being made in regard to the stratigraphy of abrupt climate change during the last glacial/ interglacial cycle some issues still need to be solved in the future.

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