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SUPPLEMENTARY MATERIAL: INTEGRATED CHALLENGER MOUND AGE MODEL

S.1 Existing U1317E stratigraphical data

In parallel with the *Lophelia pertusa* (cold-water coral) strontium isotope chronology by Kano et al. (2007), *Globigerina bulloides* (planktonic foraminifer) oxygen isotopes (Sakai et al., 2009) and sediment magnetic inclination records (Foubert and Henriet, 2009) have been used to develop an age model for the Hole U1317E Challenger Mound sediment sequence. Foubert and Henriet (2009) defined a series of magnetostratigraphic tiepoints, including the geomagnetic polarity reversals of the Brunhes, Matuyama, Olduvai, Réunion and Gauss (Sub-)Chrons, suggesting a Late-Pleistocene (< 0.78 Ma) to Late-Pliocene (> 2.58 Ma) age for the Challenger Mound sediment sequence (see Foubert and Henriet (2009) for a detailed discussion). Overall, this (sediment-based) magnetostratigraphic age model correlates well with the (coral-based) U1317E strontium isotope chronology compiled by Kano et al. (2007). The latter presents *L. pertusa* ages from ca. 0.57 Ma (top) till 2.70 Ma (mound base; excluding error bars) and indicates the presence of a significant hiatus ('mound crisis': ca. 1. 67 – 1.03 Ma, excluding error bars) between 23.66 metres below sea floor (mbsf) and 21.32 mbsf (Fig. S1). High-resolution sedimentological analyses by Thierens et al. (2010) reveal the presence of a distinct sedimentological shift around 23.4 mbsf, which seems to confirm the Kano et al. (2007) 'mound crisis event' in the sediment record. In contrast to Foubert and Henriet (2009), oxygen isotope stratigraphic work by Sakai et al. (2009) argues for a slightly younger Early-Pleistocene sequence below the mound crisis unconformity, corresponding to marine isotope stage (MIS) 92 to 72 (ca. 2.27 - 1.82 Ma). In their scenario, all upper mound sediments (i.e. above the intra-mound unconformity) should be placed in the Middle-Pleistocene MIS 19 and 18 (ca. 0.8 – 0.7 Ma). However, the topmost U1317E sediments (0 – 0.02 mbsf) have now been radiocarbon dated to 1450 ± 95 cal yr BP (Thierens et al., 2010), indicating a recent (Holocene) age for the top of the mound sequence.

At present, a comprehensive U1317E Challenger Mound sediment stratigraphy is lacking. Therefore, as will be discussed in the next sections, this study first of all improves the age constraints on the U1317E mound sediments by presenting a series of additional, biostratigraphic age tiepoints (Section S.2), which are then incorporated in an integrated age model for the (Hole U1317E) Challenger Mound sequence (Section S.3).

S.2 U1317E biostratigraphy

As summarised in Table S1, several calcareous nannofossil and planktonic foraminifer biostratigraphic events, spanning the Holocene/Late-Pleistocene to Late-Pliocene, are identified in the U1317E mound sequence.

Most CN13 to CN15 Early- to Late-Pleistocene (< 1.9 Ma) nannofossil datums (cf. de Kaenel et al., 1999; Okada and Burky, 1980; Raffi et al., 2006), could be recognised in the top ca. 25 m of the record. There, single samples often contain multiple biostratigraphic datums (e.g. at 22.78 mbsf or 24.53 mbsf), possibly due to a limited sampling resolution or the presence of unconformities in the sedimentary sequence (see also Section S.3; Table S1). Earlier (CN12b-d) Early-Pleistocene nannofossil bioevents prove more difficult to trace in U1317E, as traditionally, nannofossil marker taxa from the warm-water genus *Discoaster* are used to divide the Pliocene - Early Pleistocene (> 1.9 Ma). Their paucity outside low latitude regions, however, limits their stratigraphical value in a mid/high latitude location such as site U1317E (51°22.8'N) (cf. Sato et al., 2004). Three *Discoaster* age markers, *D. brouweri, D. triradiatus, and D. surculus*, are observed in the Challenger Mound record (34.22 - 147.16 mbsf), although only in sporadic occurrences and often poorly preserved (Supplementary Table ST1). Considering this and given the common occurrence of reworked (Pliocene – Cretaceous) nannofossils (Table ST1) and the overall highly dynamic sedimentary environment of the Challenger Mound (Thierens et al., 2010), it cannot be excluded that U1317E *Discoaster* occurrences are the result of reworking. Therefore, *Discoaster* spp. are not considered to provide reliable age datums in this study. In general, due to potential reworking issues, all low abundance occurrences should be interpreted with great caution. For a similar reason,

Table S1 U1317E calcareous nannofossil and planktonic foraminifer biostratigraphic datums. Age markers used to construct this study's integrated sediment stratigraphy are in bold; dates used are marked with an asterisk. LO = last occurrence; FO = first occurrence; LCO = last consistent occurrence; FCO = first consistent occurrence; FAO = first abundant occurrence. All depths are in corrected metres below seafloor (mbsf).

Biostratigraphic datum (this study)	Age (Ma)[a]	Age (Ma)[b]	Age (Ma)[c]	Age (Ma)[d]	Age (Ma)[e]	U1317E depth (mbsf)	IODP Exp. 307 sample code	Confidence
LO *Emiliania huxleyi*	**present**	**present**				**0.68**	**307-U1317E-1H-1-68**	**high**
FO *Emiliania huxleyi*	***0.265**					**0.68**	**307-U1317E-1H-1-68**	**high**
LO *Pseudoemiliania lacunosa*	***0.440**					**11.56**	**307-U1317E-2H-4-60**	**high**
LO *Pseudoemiliania lacunosa* (>7 µm)		***0.439**				**11.56**	**307-U1317E-2H-4-60**	**high**
LO *Crenalithus asanoi* (>6.5 µm)		0.781				22.78	307-U1317E-3H-5-77	moderate
LCO *Crenalithus asanoi*	0.905					22.78	307-U1317E-3H-5-77	moderate
Reentrance medium *Gephyrocapsa* (>4 µm) + FO *Gephyrocapsa* sp.3	***1.007**					**22.78**	**307-U1317E-3H-5-77**	**high**
FO *Crenalithus asanoi* (>6.5 µm)		***1.122**				**23.34**	**307-U1317E-3H-5-135**	**moderate**
FCO *Crenalithus asanoi*	***1.136**					**23.34**	**307-U1317E-3H-5-135**	**moderate**
LO *Helicosphaera sellii*		1.246				24.53	307-U1317E-3H-6-107	moderate
LCO *Helicosphaera sellii*		1.276				24.53	307-U1317E-3H-6-107	moderate
LO *Calcidiscus macintyrei* (>11 µm)	1.60	1.619				24.53	307-U1317E-3H-6-107	high
FO *Gephyrocapsa* oceanica (>4 µm)		***1.719**				**24.53**	**307-U1317E-3H-6-107**	**moderate-high**
FO *Gephyrocapsa* caribbeanica (>4 µm)		***1.726**				**24.53**	**307-U1317E-3H-6-107**	**moderate-high**
LO *Discoaster triradiatus*		1.954				34.22	307-U1317E-4H-6-137	low °
LO *Discoaster brouweri*	1.926	1.954				37.67	307-U1317E-5H-2-107	low °
FAO encrusted *Neogloboquadrina pachyderma* sinistral [f]					***1.78**	**43.80**	**307-U1317E-5H-6-143**	**high**
FO gephyrocapsid				~1.86 - 1.95		46.97	307-U1317E-6H-2-77	moderate
FO *Globorotalia inflata*					***2.09**	**60.12**	**307-U1317E-7H-5-3**	**high**
LO *Discoaster surculus*	2.485					106.71	307-U1317E-12H-4-75	low °
Datum A			***2.74**			**146.31**	**307-U1317E-16H-5-98**	**moderate**

[a] Raffi et al. (2006); [b] de Kaenel et al. (2001); [c] Sato et al. (2004); [d] Rio (1982); [e] Weaver and Clement (1986)
[f] Below 43.80 mbsf, sinistrally-coiled N. pachyderma occurs, but predominantly in its non-encrusted form; ° likely reworked

we consider first (consistent) occurrences of species/genera to yield overall more reliable age tiepoints than their (low abundance/sporadic) last occurrences (see Table S1).

At 146.31- 145.46 mbsf, the *Reticulofenestra* spp. – *Coccolithus pelagicus* dominance shift in the nannofossil assemblage represents the 'Datum A' event (Sato and Kameo, 1996; Sato et al., 2004). As discussed by Sato and Kameo (1996) and Sato et al. (2004), this specific (high-latitudinal) floral assemblage change is thought to be linked to the southward migration of most nannofossil taxa, except the cold-water species *C. pelagicus*, as glaciations started to intensify in the (high-latitudinal) Northern Hemisphere. Datum A is correlated with the LO of *D. tamalis* at 2.74 Ma (Sato and Kameo, 1996; Sato et al., 2004) and has been recognised in the North Atlantic DSDP/IODP Sites 611 (52°50.5' N) and 609/ U1308 (49° 52.7'N), besides multiple DSDP/ODP locations in the Arctic Ocean (Channell et al., 2005; Sato and Kameo, 1996; Sato et al., 2004). Hence, despite the lack of reliable traditional nannofossil marker taxa for the (Late) Pliocene – Early Pleistocene, Datum A suggests the presence of (Late-) Pliocene (> 2.74 Ma) sediments in the lower ca. 10 m of the (U1317E) Challenger Mound.

The U1317E planktonic foraminifer assemblage contains two significant Early-Pleistocene bioevents, associated with the FO of *Globorotalia inflata* (2.09 Ma) and the FAO of encrusted *Neogloboquadrina pachyderma* s (ca. 1.78 Ma) in the temperate/sub-polar North Atlantic Ocean (Weaver and Clement, 1986) (Table S1). The top ca. 44 m of the U1317E sequence can therefore be positioned in the *N. pachyderma* s biostratigraphic zone (1.78 Ma – present), while sediments between 43.80 and 60.12 mbsf demarcate the *G. inflata* zone (2.09 – 1.78 Ma) (*sensu* Weaver and Clement, 1986). As not a single specimen of *Neogloboquadrina atlantica* (sinistral or dextral) was observed in the U1317E planktonic fauna, all sediments below 60.12 mbsf should be placed in the biostratigraphic *G. bulloides* zone, which ranges from 2.09 Ma (FO *G. inflata*) to 2.4 – 2.3 Ma (LO *N. atlantica*; Flower, 1999; Weaver and Clement, 1986). Hence, the U1317E planktonic foraminifer fauna implies a maximum, Early-Pleistocene age of 2.3 – 2.4 Ma for the base of the Challenger Mound sediment sequence (cf. Huvenne et al. (2009) for Hole U1317C).

S.3 Integrated sediment chronostratigraphy

Overall, the biostratigraphic datums identified in this study correlate well with the sediment-based stratigraphical data provided by Foubert and Henriet (2009) and Thierens et al. (2010) (Fig. S1, Table 1).

At the top of the U1317E sequence, the range of *Emiliania huxleyi* (0. 265 Ma – present; Raffi et al., 2006) confirms the sub-recent age of the latest Challenger Mound deposits (cf. Thierens et al., 2010), while the nannofossil age markers at 11.56 mbsf (0.44 Ma) and 22.78 mbsf (1.01 Ma) support the magnetostratigraphic timeframe proposed for the upper part of U1317E (Fig. S1). The significant (nannofossil) age difference between the deposits at 24.53 mbsf (ca. 1.7 Ma) and those at 23.34 mbsf (1.1 Ma) (Fig. S1, Table S1), in combination with the concentration of nannofossil bioevents in the sample at 24.53 mbsf (Table S1), agrees with the proposed presence of a considerable, 'mound crisis' unconformity around ca. 23.4 mbsf (Thierens et al., 2010). Moreover, the ages provided by the biostratigraphic markers fall well within the analytical limits of the Kano et al. (2007) *L. pertusa* strontium isotope ages delimiting this unconformity (Fig. S1). Also in the lower mound sequence (unit M1), the magnetostratigraphy and biostratigraphy prove generally consistent. The FAO of encrusted *N. pachyderma* s marks the top of the Olduvai Chron, while the FO of *G. inflata* is recognised between the Olduvai and Réunion chronozones (Fig. S1) (cf. Lourens et al., 1996; Weaver and Clement, 1986). The FO of the genus *Gephyrocapsa*, at 46.97 mbsf, further confirms the mid-lower extent of the Olduvai Chron, as suggested by Rio (1982) (Fig. S1).

A minor discrepancy exists between the timing and location of the 1.68 Ma Gisla Event, a small positive inclination event observed at 27.43 mbsf (Foubert and Henriet, 2009), and that of the 1.72 Ma nannofossil age tiepoint at 24.53 mbsf. A more significant stratigraphical divergence arises at the base of the U1317E mound sequence, where different proxies suggest ages ranging from less than 2.3 Ma (absence of *N. atlantica*) to over 2.74 Ma (Datum A nannofossil event) (see Section S.2). However, besides the *Reticulofenestra* spp. – *C. pelagicus* nannofossil dominance shift (Section S.2), both the significantly lower abundance of warm-water planktonic foraminifer taxa above ca. 150 mbsf (see Section 6.3) and the presence of multiple ice-rafted layers between 143 and 145 mbsf (Thierens et al., 2012) provide evidence for a distinct cooling and glaciation event around 145 – 146 mbsf. Hence,

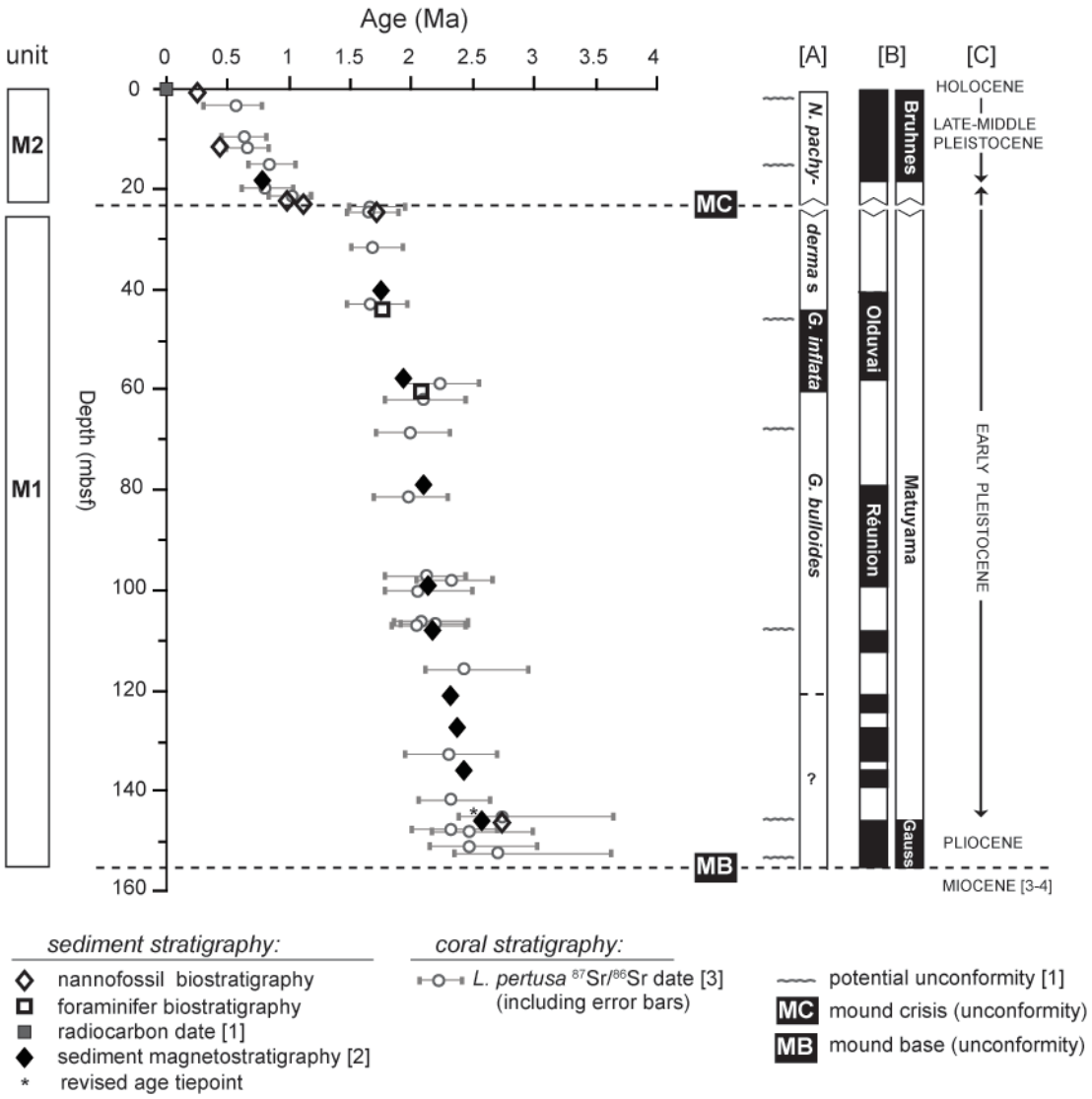

Figure S1 Integrated U1317E Challenger Mound age model. Compilation of sediment- and coral-based stratigraphical tiepoints for the U1317E mound sequence, as defined in this study, [1] Thierens et al. (2010), [2] Foubert and Henriet (2009) and [3] Kano et al. (2007). Submound stratigraphical data from [3] Kano et al. (2007) and [4] Louwye et al. (2008). [A] = planktonic foraminifer biozones (sensu Weaver and Clement, 1986); [B] = magnetostratigraphic chronozones; [C] = chronostratigraphic (sub-)series (sensu Gibbard et al., 2010). Sedimentologically-defined potential unconformities (Thierens et al., 2010) are added for reference. All depths are in corrected metres below seafloor (mbsf).

although it necessitates the re-evaluation of the Matuyama – Gauss palaeo-magnetic transition (which can be repositioned to 145.85 mbsf ; Foubert, pers.comm.), independent palaeo-climatic evidence from both the biogenic and siliciclastic sediment fraction is present in support of the Datum A nannofossil event. Therefore, in this study, a slightly older, Pliocene (> 2.74 Ma) age is proposed for the basal Challenger Mound deposits. Considering all other U1317E stratigraphical data and given its identification in neighbouring North Atlantic sites on, e.g., the Feni Drift (Weaver and Clement, 1986) and the Goban Spur (Pujol and Duprat, 1985), the absence of *N. atlantica* (LO at 2.4 – 2.3 Ma) in the Early-Pleistocene to Pliocene Challenger Mound deposits is puzzling.

Overall, as visualised in Figure S1, the integrated age model proposed in this study provides a refined, multiproxy age estimate for the U1317E sediments, consistent with the Kano et al. (2007) cold-water coral chronology. Only in the top ca. 12m of the core, sediment-derived ages are at the younger end of the coral age range (ca. 200-250 ka younger; Fig. S1). However, the Sr isotope chronological uncertainty increases significantly in this time interval. Sedimentologically-defined potential unconformities (Thierens et al., 2010) (Fig. S1) could, however, not be confirmed, as their timespan is

most likely too short to be resolved by the age model.

REFERENCES

Channell, J.E.T., Kanamatsu, T., Sato, T., Stein, R., Alvares Zarikian, C.A., Malone, M.J., the Expedition 303/306 Scientists, 2005. Proceedings of the Integrated Ocean Drilling Program, Volume 303/306. College Station TX (Integrated Ocean Drilling Program Management International, Inc.), doi:10.2204/iodp.proc.303306.108.2006.

de Kaenel, E., Siesser, W.G., Murat, A., 1999. Pleistocene Calcareous Nannofossil Biostratigraphy and the Western Sapropels, Sites 974 to 977 and 979. In: R. Zahn, M.C. Comas, A. Klaus (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, 161. College Station, TX (Ocean Drilling Program), pp. 159–183.

Flower, B.P., 1999. Data Report: Planktonic foraminifers from the subpolar North Atlantic and Nordic Seas: sites 980-987 and 907. In: M.E. Raymo, E. Jansen, P. Blum, T.D. Herbert (Eds.), Proceedings of the Ocean Drilling Program, Scientific Results, 162. College Station, TX (Ocean Drilling Program), pp. 19-34.

Foubert, A., Henriet, J.P., 2009. Nature and significance of the recent carbonate mound record: the Mound Challenger Code. Springer-Verlag, Heidelberg, 350 pp.

Gibbard, P.L., Head, M.J., Walker, M.J.C., the Subcommission on Quaternary Stratigraphy, 2010. Formal ratification of the Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma. Journal of Quaternary Science 25, 96-102.

Huvenne, V.A.I., Van Rooij, D., De Mol, B., Thierens, M., O'Donnell, R., Foubert, A., 2009. Sediment dynamics and palaeo-environmental context at key stages in the Challenger cold-water coral mound formation: Clues from sediment deposits at the mound base. Deep-Sea Research I 56, 2263-2280.

Kano, A., Ferdelman, T.G., Williams, T., Henriet, J.-P., Ishikawa, T., Kawagoe, N., Takashima, C., Kakizaki, Y., Abe, K., Sakai, S., Browning, E.L., Li, X., IODP Exp.307 Scientists, 2007. Age constraints on the origin and growth history of a deep-water coral mound in the northeast Atlantic drilled during Integrated Ocean Drilling Program Expedition 307. Geology 35, 1051-1054.

Louwye, S., Foubert, A., Mertens, K., Van Rooij, D., IODP Exp. 307 scientific party, 2008. Integrated stratigraphy and palaeoecology of the Lower and Middle Miocene of Porcupine Basin. Geological Magazine 145, 321-344.

Lourens, L.J., Antonarakou, A., Hilgen, F.J., Van Hoof, A.A.M., Vergnaud-Grazzini, C., Zachariasse, W.J., 1996. Evaluation of the Plio-Pleistocene astronomical timescale. Paleoceanography 11, 391-414.

Okada, H., Burky, D., 1980. Supplementary modification and introduction of code numbers to the Low Latitude Coccolith Biostratigraphy Zonation (Bukry, 1973, 1975). Marine Micropaleontology 51, 321-325.

Pujol, C., Duprat, J., 1985. Quaternary and Pliocene planktonic foraminifers of the Northeastern Atlantic (Goban Spur), Deep Sea Drilling Project Leg 80. In: P.C. Graciansky, C.W. de Poag, et al. (Eds.), Init. Repts. DSDP, 80, Washington (U.S. Govt. Printing Office), pp. 683-723.

Raffi, I., Backman, J., Fornaciari, E., Pälike, H., Rio, D., Lourens, L., Hilgen, F., 2006. A review of calcareous nannofossil astrobiochronology encompassing the past 25 million years. Quaternary Science Reviews 25, 3113-3137.

Rio, D., 1982. The fossil distribution of Coccolithophore Genus *Gephyrocapsa* Kamptner and related Plio-Pleistocene Chronostratigraphic problems. In: W.L. Prell, J.V. Gardner, et al. (Eds.), Init. Repts. DSDP, 68. Washington (U.S. Govt. Printing Office), pp. 325-343.

Sakai, S., Kano, A., Abe, K., 2009. Origin, glacial-interglacial responses, and controlling factors of a cold-water coral mound in NE Atlantic. Paleoceanography 24, PA2213, doi:10.1029/2008PA001695.

Sato, T., Kameo, K., 1996. Pliocene to Quaternary calcareous nannofossil biostratigraphy of the Arctic Ocean, with reference to late Pliocene glaciation. Proceedings of the Ocean Drilling Program, Scientific Results, v. 151, 39-59.

Sato, T., Yuguchi, S., Takayama, T., Kameo, K., 2004. Drastic change in the geographical distribution of the cold-water nannofossil *Coccolithus pelagicus* (Wallich) Schiller at 2.74 Ma in the late Pliocene, with special reference to glaciation in the Arctic Ocean. Marine Micropaleontology 52, 181-193.

Thierens, M., Pirlet, H., Colin, C., Latruwe, K., Vanhaecke, F., Lee, J.R., Stuut, J.-B., Titschack, J., Huvenne, V.A.I., Dorschel, B., Wheeler, A.J., Henriet, J.-P., 2012. Ice-rafting from the British-Irish ice sheet since the earliest Pleistocene (2.6 million years ago): implications for long-term mid-latitudinal ice-sheet growth in the North Atlantic region. Quaternary Science Reviews 44, 229-240.

Thierens, M., Titschack, J., Dorschel, B., Huvenne, V.A.I., Wheeler, A.J., Stuut, J.-B., O'Donnell, R., 2010. The 2.6 Ma depositional sequence from the Challenger cold-water coral carbonate mound (IODP Exp. 307): Sediment contributors and hydrodynamic palaeo-environments. Marine Geology 271, 260-277.

Weaver, P.E., Clement, B.M., 1986. Synchroneity of Pliocene planktonic foraminiferal datums in the North Atlantic. Marine Micropaleontology 10, 295-307.