An emerging palaeoceanographic ‘missing link’: multidisciplinary study of rarely recovered parts of deep-sea Santonian–Campanian transition from Shatsky Rise

A. ANDO1,2*, S. C. WOODARD3, H. F. EVANS4, K. LITTLER3, S. HERRMANN5, K. G. MACLEOD7, S. KIM1, B.-K. KHIM1, S. A. ROBINSON5 & B. T. HUBER2

1BK21 Coastal Environmental System School, Department of Oceanography, Pusan National University, Busan 609-735, South Korea
2Department of Paleobiology, National Museum of Natural History, Smithsonian Institution, PO Box 37012, MRC 121, Washington, DC 20033-7012, USA
3Department of Oceanography, Texas A&M University, 3146 TAMU, College Station, TX 77843, USA
4Lamont-Doherty Earth Observatory of Columbia University, 61 Route 9W, Palisades, NY 10964, USA
5Department of Earth Sciences, University College London, Gower Street, London WC1E 6BT, UK
6Department of Earth Sciences, Geological Institute, ETH Zurich, Sonneeggstrasse 5, CH-8092 Zurich, Switzerland
7Department of Geological Sciences, University of Missouri, Columbia, MO 65211-1380, USA

*Corresponding author (e-mail: AndoA@si.edu)

The Cretaceous deep-sea record of the Santonian–Campanian transition is commonly interrupted by an extensive unconformity (representing <10 Myr of hiatus). The resultant palaeoceanographic gap can now be partly bridged by a recent short core of pelagic ooze from Shatsky Rise (Integrated Ocean Drilling Program (IODP) Site U1348), with precise multidisciplinary age constraints developed herein. New oxygen isotope data from very well-preserved benthic foraminifera, together with accurately compiled comparable benthic data from previous Pacific deep-sea sections, exhibit a large (c. +1‰) early Campanian shift. We propose the Santonian–Campanian climatic transition was not gradual but was the first major cooling step after sustained mid-Cretaceous hothouse conditions.

Supplementary material: Detailed analytical methods including biostratigraphic notes and Sr isotopic chronology, supplementary figures (locality map; additional geochemical, isotopic and micropalaeontological results; palaeomagnetic results; global Sr isotope compilation and age model; benthic foraminiferal stable isotope compilation), tables of microfossil occurrences and numerical data are available at http://www.geolsoc.org.uk/SUP18598.

Unconformities in the pelagic sedimentary record are a major obstacle in reconstructing palaeoceanographic histories, yet they also can be robust physical evidence of major shifts in past deep-water properties. Hence, unconformities can convey crucial palaeoceanographic information as long as their causal mechanism (i.e. hiatus) is reasonably explained by the data from coeval stratigraphically complete sections. However, if the spatiotemporal extent of hiatus was so extensive that a certain age of stratigraphic interval was totally erased from the global pelagic sedimentary record, it becomes impossible to reconstruct any changes in the deep-sea environment at that time. Although generally overlooked, this situation has been a serious problem in Late Cretaceous palaeoceanography.

A pronounced break exists in the deep-sea sedimentary record at the Santonian–Campanian (S–C) transition that cannot be ascribed simply to technical artefacts of drilling. Sliter (1992, 1995) summarized the chronostratigraphic integrity of Cretaceous Deep Sea Drilling Project (DSDP)–Ocean Drilling Program (ODP) sites in the Pacific basin based on planktonic foraminifera and illustrated the widespread hiatus around the Santonian/Campanian (S/C) boundary (c. 83.5 Ma). Recent Sr isotopic evidence from DSDP Site 463 showed that the S–C hiatus in the central Pacific potentially lasted up to 10 Myr (Ando et al. 2009). Huber (1992), using calcareous microfossil occurrences of multiple southern high-latitude DSDP–ODP sites, documented a ‘Southern Ocean hiatus’ more or less coincident with the Pacific S–C hiatus. Furthermore, the imperfect nature of the S–C sedimentary record has been highlighted from several North Atlantic deep-sea sites (Huber et al. 2002; MacLeod et al. 2011; Robinson & Vance 2012).

One consequence of such ubiquitous S–C unconformities is a significant data gap in global benthic foraminiferal oxygen isotope (δ18O) compilations (e.g. Cramer et al. 2009). Accordingly, the timing and tempo of S–C palaeoecological evolution, and its relationship to palaeoceanographic and biotic changes, remain unknown. The latest benthic δ18O compilation, by Friedrich et al. (2012), shows no discernible gap at the S–C transition, but this reconstruction should be viewed with caution because of uncertainties in their age-models, and their subjective treatment of benthic foraminiferal vital effects (see discussion below). It should be noted that the δ18O profile of excellently preserved foraminifera at South Atlantic DSDP Site 511 was often depicted to be stratigraphically complete across the S/C boundary; however, examination of the available palaeoceanographic record suggests that deposition at this site predated the S/C boundary (see Huber et al. 2002). Sites with a complete S–C transition have been reported from off NW Australia (ODP Site 762) and on land in the Mediterranean Tethys (e.g. Petrizzo et al. 2011), but the available materials are diagnostically affected.

IODP Site U1348. New material recovered through Integrated Ocean Drilling Program (IODP) Expedition 324 provides an unprecedented opportunity to address the issues outlined above. Site U1348 was cored on the northern flank of Tamu Massif (34°24.940′N, 159°22.907′E; water depth 3264 m), an area of Shatsky Rise (NW Pacific) unexplored by past DSDP–ODP legs. The thin Cretaceous
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(Aptian–Campanian) sediment cover of pelagic carbonates was found to be unconsolidated and thus described as ‘ooze’, and to contain varying amounts of chert (Expedition 324 Scientists 2010). At 80 Ma, this site was situated around 2500–3000 m palaeowater-depth assuming normal lithospheric subsidence.

Site U1348-Core 2R contains 1.4 m of monotonous pale yellow nannofossil ooze, from which very well-preserved matrix-free foraminiferal specimens are readily isolated by gentle spray washing only. Two samples studied onboard yielded a typical Santonian planktonic foraminiferal assemblage at the bottom of this core and a Campanian assemblage at the top (Expedition 324 Scientists 2010). For the post-cruise study, samples were taken at high resolution (10 cm spacing) and analysed to generate micropalaeontological, geochemical and palaeomagnetic data.

Multidisciplinary chronological results. Detailed examination of well-preserved planktonic foraminifera (often retaining delicate umbilical features) confirms the Santonian to Campanian age of Site U1348-Core 2R, in which a drastic assemblage compositional change is recognized across the boundary between Sections CC and 1 (85.3 m below seafloor (mbsf)) (Fig. 1). U1348-2R-CC is in the Dicarinella asymetrica Zone, yielding such Santonian representatives as D. asymetrica and Sigalia rugocostata with species of Marginotruncana. The age is further narrowed to the late Santonian based on the presence of Ventilabrella eggeri and Hendersonites carinatus (e.g. Nederbragt 1991). In contrast, the assemblage in U1348-2R-1 contains typical Campanian taxa of Globotruncanita and Globotruncana, both of which are high in abundance, large-sized, and diverse. Biostratigraphic subdivision of U1348-2R-1 can be facilitated by the species of Globotruncanita (in the absence of Radotruncana calcarata), such that the lower part is marked by the common occurrence of G’ta elevata (G’ta elevata Zone (or Contusotruncana plummerae Zone, sensu Petrizzo et al. 2011); early to middle Campanian), whereas the upper part represents the co-occurrence of G’ta stuarti and G’ta subspinosa (late Campanian). Nannofossils from this interval represent no marked changes in the major assemblage composition and preservation state (with common etching and/or fragmentation). Some age-diagnostic taxa allow for zonal assignments (CC14–CC24), which are consistent with the planktonic foraminiferal age.

With the primary microfossil ages constrained, Sr isotopic and palaeomagnetic data serve as precise means of chronology. In the absence of Radotruncana calcarata, such that the lower part is marked by the common occurrence of G’ta elevata (G’ta elevata Zone (or Contusotruncana plummerae Zone, sensu Petrizzo et al. 2011); early to middle Campanian), whereas the upper part represents the co-occurrence of G’ta stuarti and G’ta subspinosa (late Campanian). Nannofossils from this interval represent no marked changes in the major assemblage composition and preservation state (with common etching and/or fragmentation). Some age-diagnostic taxa allow for zonal assignments (CC14–CC24), which are consistent with the planktonic foraminiferal age.
The δ18O trends for both bulk carbonates and benthic foraminifera document a large +1.0% shift over the examined interval (Fig. 1). Benthic foraminiferal specimens are very well preserved with dully translucent ‘pearly’ tests (Fig. 1), showing fairly minor surface dissolution and/or recrystallization. The sedimentary CaCO3 contents are very high (93–97 wt%); in such a case recrystallization is known to be often significant (e.g. Pearson et al. 2007), but this is not the case for U1348 benthic foraminifera.

Of the six benthic taxa selected for analysis, Aragonia is the only group available from almost all samples. This taxon has not been widely used in palaeoceanographic studies, but we document it as the taxon (Katz et al. 2003; Ando et al. 2006). Three other groups with higher δ13C values, Nuttallides, are generally interpreted as living epifaunally. Their negative δ18O offsets relative to the Aragonia–Oridorsalis δ18O profile as a faithful δ18O recorder, including a widely used taxon Nuttallides, are generally interpreted as living epifaunally. Their negative δ18O offsets relative to the Aragonia–Oridorsalis δ18O profile, an expression of the isotope-disequilibrium vital effects in epifauna characterized by higher metabolic rates (e.g. Friedrich et al. 2006). Three other groups with higher δ13C values, including the Campanian–Maastrichtian assemblage (Friedrich et al. 2006).

Discussion. Site U1348-Core 2R (albeit limited stratigraphically) represents the first, superior sedimentary record of the deep-sea S–C transition, with a robust chronology, very good preservation, and a fully open-ocean setting. Most importantly, now we have new definitive control points in the Late Cretaceous deep-sea δ18O evolution. Figure 3 shows an updated benthic foraminiferal δ13C compilation for central Pacific DSDP–IODP Sites 305, 463 and U1348, for which special attention is given to objective age modelling by means of Sr isotope stratigraphy, proper data corrections for disequilibrium δ18O precipitation, and additional corrections for the possible effect of inter-site water-depth differences.

Many of new U1348 δ18O data fall within the c. 7 Myr S–C gap evident in the pre-existing datasets. It appears that the S–C transition marked a major step in δ18O (Fig. 3b), when the baseline shifted to 0‰ or greater after c. 25 Myr of universally negative benthic δ18O values since the Albian (e.g. Friedrich et al. 2012). In other words, the mid-Cretaceous hothouse persisted to the latest Santonian, and then switched to cool greenhouse (Huber et al. 2002) during the early Campanian. The exact timing and pacing of this climatic transition remain unresolvable, but the shift should be within the first 3–4 Myr of the Campanian.

Friedrich et al. (2012) presented a comprehensive benthic δ18O compilation showing a gradual trend across the S–C transition. However, their age-model information on the deep-sea sites used for δ18O compilation (Friedrich et al. 2012, table DR1) is literature

![Fig. 2. Graphic summary of probable age ranges of U1348-Core 2R sediments against GTS2004 (Ogg et al. 2004) combined with the standard Sr isotope curve (modified in this study). Superimposed on 87Sr/86Sr data are a fifth-order polynomial (90–65 Ma) and its confidence limits (=±1 standard deviation of residuals; grey curve). The Contusotruncana plummerae Zone is adopted from Petrizzo et al. (2011), but its originally defined base (open arrowhead) would require further examination for inter-site diachronicity as discussed elsewhere.](Image)

![Fig. 3. (a) Updated Late Cretaceous benthic foraminiferal δ18O compilation for the central Pacific. Data are from DSDP–IODP Sites 305, 463 and U1348, and also corrected for Sr isotope stratigraphy, isotope disequilibrium and inter-site water-depth differences. (b) Same dataset as for (a) but an ad hoc correction factor of +0.3‰ (= c. 1.5°C) is applied to all Site 463 data to accommodate probable water depth-related δ18O offset relative to Site U1348.](Image)
citations only, without a list of datum events adopted. With specific reference to Sites 305 and 463, it is unclear how Friedrich et al. (2012) could plot the δ18O data so evenly through the Santonian–Campanian interval. Furthermore, despite the presence of a systematic δ18O–δ13C offset between the taxa used (Globorotalia v. Praebulimina), those researchers did not make the isotope disequilibrium correction, which is another technical artefact that resulted in somewhat scattered, gradual S–C δ18O compilation. Although Friedrich et al. (2012) is commended for adding numerous new data points to the Late Cretaceous δ18O database, we conclude that a stepwise δ18O evolution for the S–C transition is reasonable and robustly supported by data, especially considering the Sr isotopic inter-site chronology developed herein.

Implications for global change study. The S–C cooling step, as illustrated by our benthic δ18O compilation, may be linked to an early Campanian reorganization of global ocean circulation in response to changing palaeoclimates and/or palaeogeography, as suggested on the basis of Nd isotopic data, albeit with lingering age uncertainty (e.g. MacLeod et al. 2011; Robinson & Vance 2012). Now this cooling episode also seems broadly coincident with the resumption of magnetic reversals after ‘superchron’ C34n (Fig. 3). These observations may elevate the significance of study of the S–C transition to a broader discipline of global change.

In this regard, it should be noted that the U1348 δ18O data from bulk carbonates (predominantly coccoliths) exhibit a +1.2‰ shift, parallelizing the benthic δ18O trend (Fig. 1). The observed bulk δ18O variation cannot be explained by the changing nannoflora or a varying extent of early recrystallization (Pearson et al. 2007), because the nannofossil assemblage, coccolith preservation, and lithology are all uniform through the examined interval. If the δ18O shift translates to a genuine palaeotemperature signal (in the absence of local palaeoceanographic control), a cooling by 5–6°C is required (e.g. Ando et al. 2010), although (sub)tropical sea-surface temperatures were probably less sensitive to greenhouse forcings (e.g. Otto-Bliesner et al. 2005). Although speculative, Antarctic glaciation and a resultant whole-ocean δ18O shift might have played a role, at least in part, in the observed surface–bottom δ18O co-variation (e.g. Miller et al. 2005).

Whatever the likelihood of glaciation, the S–C transition is worthy of more attention as a critical period of global change during the Cretaceous greenhouse. Further scrutiny of available S–C deep-sea and continental sedimentary records is necessary in terms of chronology, δ18O variation and/or sea-level change. Linking all of the palaeoenvironmental observations with a precise chronology in future work would allow the construction of a unified view on the causes and consequences of one of Earth’s major climatic shifts.

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