Off-shelf sedimentary record of recurring global sea-level changes during the Plio-Pleistocene: evidence from the cyclic fills of exhumed slope systems in central Italy

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The markedly cyclic sedimentary successions of four late Pliocene to early Pleistocene slope turbidite systems exposed in eastern central Italy have been resolved into 31 high-frequency sequences. Chronological constraints from biostratigraphy and magnetostratigraphy indicate that these successions form a composite, partially overlapping stratigraphic record and sequence-bounding surfaces can be convincingly correlated with glacial oxygen isotope stages G2–60 (c. 2.65–1.7 Ma) inclusive. The studied successions, therefore, preserve an extraordinary and legible record of recurring, orbitally dictated glacio-eustatic sea-level fluctuations and provide an unprecedented opportunity to examine the deep-water sedimentary response to such high-frequency changes from an outcrop perspective.

Supplementary material: Sedimentological attributes of lithofacies identified in the studied successions are available at www.geolsoc.org.uk/SUP18549.

The onset of significant Northern Hemisphere glaciation from 3.0 to 2.5 Ma initiated a pattern of growth and decay of major continental ice sheets that resulted in rapid sea-level changes. Throughout the late Pliocene and early Pleistocene, these changes in sea level were dominated by the 41 ka periodicity of orbital obliquity and operated with magnitudes ranging between 25 ± 10 and 110 ± 20 m (Naish 1997). Over the last two decades, a wealth of outcrop-based studies have pointed out that, typically, the resulting shallow-marine stratigraphic record is outwardly cyclothemical, with each cyclothem representing a single Milankovitch oscillation in sea level (e.g. Clifton et al. 1988; Haywick et al. 1992; Kitamura et al. 1994; Naish et al. 1998; Massari et al. 2002; Abbott et al. 2005; Cantalamessa et al. 2005, 2006; Di Celma et al. 2005). In contrast, far fewer outcrop studies have documented the sedimentological expression of such high-frequency sea-level changes in off-shelf, slope settings (Ito & Katsura 1992; Pickering et al. 1999). One reason for this bias toward the study of unconformity-bound strata of shelf origin is the rarity of suitable late Neogene deep-water successions, which in most parts of the world underlie flooded continental margins. From this perspective, the markedly cyclic late Pliocene to early Pleistocene clastic successions exposed onland in eastern central Italy are particularly well suited, offering a unique opportunity to investigate the outcrop stratigraphy of deep-water depositional sequences deposited during glacio-eustatic changes in sea level. The objectives of this paper are to (1) present a synthesis of the stratigraphy and chronology of these turbidite successions, which form a deep-water composite stratigraphic record spanning the interval from just below the Gauss–Matuyama transition to above the currently defined Gelasian–Calabrian boundary, and (2) establish a precise correlation between single sequences and the glacio-eustatic sea-level changes inferred from the Pliocene to early Pleistocene oxygen isotope record.

Geological setting and stratigraphy. The Central Apennine foreland basin system assumed its present configuration during the Pliocene and early Pleistocene (Gelasian) when, as a result of the progressive propagation toward the east of the Apennine thrust fronts, the previous foredeep was fragmented into piggy-back basins (i.e. the Peri-Adriatic basin) and a more external foredeep located ahead of the outermost thrust front (Fig. 1; Artoni 2007). The Gelasian portion of the Peri-Adriatic basin fill, now exposed onshore as a consequence of rapid tectonic uplift during the middle Pleistocene to Holocene, includes most of the stratigraphic interval of interest for this study. It consists of a thick succession of hemipelagic slope mudstones punctuated by the coarse-grained infill of a series of submarine canyons that acted as major conduits for transport of Apennine-derived clastic detritus into the adjacent deep-water basin. From oldest to youngest, the main canyon fills are the Monte Ascensione, Castignano, Offida and Colle Montarone systems. A total of six principal turbidite and debris depositional elements can be delineated within these successions: (1) conglomerate-dominated channel-complex; (2) sandstone-dominated channel-complex; (3) sandy braid plain; (4) frontal splay; (5) levee-overbank; (6) mudstone-rich mass-transport deposits. An abiding feature of these canyon-fill strata is their markedly cyclic pattern of deposition (Cantalamessa et al. 2009), with component depositional elements succeeding one another in well ordered and stratigraphically consistent vertical trends to form recurrent successions of unconformity-bound fining-upward units. Each sequence consists of a basal sequence boundary generated during a period of erosion and complete sediment bypass; (2) a lowstand systems tract composed of channel-filling conglomerates and sandstones with or without laterally adjacent levee-overbank heterolithic deposits (Motif-1 and Motif-2) or, alternatively, a medium- to thick-bedded tabular sandstones of a frontal splay (Motif-3); (3) a transgressive to forced regressive systems tract made up of pebbly mudstones and chaotic beds of mass-transport deposits (Motif-1) or, alternatively, a transgressive systems tract comprising a fining- and thinning-upward heterolithic succession (Motif-2 and Motif-3). Outcrop characteristics of sequence boundaries, depositional elements and their associated lithofacies
have been described and interpreted by Cantalamessa et al. (2009), Di Celma et al. (2010) and Di Celma (2011). In this paper, sequences are designated alphabetically starting with an abbreviation for the slope system (MA, CST, O and CM for Monte Ascensione, Castignano, Offida and Colle Montaroni, respectively) followed by a number, representing the sequence number in ascending order, and a numeric subscript that refers to the architectural motif.

Chronostratigraphic framework and correlations to oxygen isotope stratigraphy. Correlation of the 31 deep-water sedimentary cycles to an independent approximation of the sea-level history in the form of an oxygen isotope curve (Lisiecki & Raymo 2005) has been undertaken to assess the potential eustatic control on the development of these sequences (Fig. 2). Critical to this attempt at correlation has been the establishment of a high-resolution chronostratigraphic framework based on a series of biostratigraphic and palaeomagnetic events that provided an adequate number of firm correlation tie points. Sequence boundaries, marking the onset of distinct cycles of canyon filling, are interpreted to have formed at, or just before, the lowest position of relative sea level, which is inferred to be a period of efficient slope sediment bypass, and have been tentatively correlated with the even-numbered (glacial) isotope stages of the oxygen isotope curve.

The sedimentary succession of the Monte Ascensione system is about 1 km thick and consists of 15 superimposed sequences. According to Cantalamessa et al. (2009), two magnetozones are represented in the lowermost portion of the Monte Ascensione system (i.e. from MA-1, to MA-5). A single normal-polarity interval encompasses the highest part of hemipelagic mudstones underlying the Monte Ascensione system and the canyon fill from the base up to the mud-prone interval of MA-2. This is followed by a long interval of reversed polarity that characterizes the canyon fill from MA-3 to MA-5. Biostratigraphic constraints allow a straightforward interpretation of these magnetic polarity zones as the upper part of the normal-polarity Gauss Chron and the lower part of the reversed-polarity Matuyama Chron. This interpretation is validated by (1) the presence of the MPL5 biozone throughout the entire section and the first appearance of some primitive specimens of Bulimina marginata in samples from the fine interval of MA-2.

The overlying strata (from MA-4 to MA-14) are constrained exclusively by detailed biostratigraphy. The samples collected for biostratigraphic analysis yielded poor microfossil assemblages that are characterized by (1) the co-occurrence of the age-diagnostic calcareous nannofossil Discoaster brouweri and benthic foraminifera B. marginata throughout the entire stratigraphic interval, (2) the presence of the planktonic foraminifera Globorotalia puncicultata only in samples of MA-6, and (3) the first occurrence of Globorotalia inflata in samples of MA-14. According to these data, sediments of the Monte Ascensione system span the time interval equivalent to Marine Isotope Stages (MIS) G2–77 (c. 2.65–2.05 Ma).

Within the Castignano system at least six successive unconformity-bounded sequences have been recognized (Di Celma et al. 2012). The chronostratigraphic frame for these turbidite strata and the surrounding hemipelagic mudstones has been constructed using age-diagnostic benthic and planktonic foraminifera. The foraminiferal assemblages from mudstones sampled below the turbiditic system contain B. basispinosa and Globorotalia crassaformis in the lower portion and B. marginata in the stratigraphically highest part. Likewise, specimens of B. basispinosa and B. marginata co-occur in the low-diversity foraminiferal assemblages characteristic of the lowermost samples recovered in the turbidite system from deposits of CST-1 and CST-2. The age-diagnostic G. puncicultata and G. inflata were not found in any of these samples, so that these assemblages can be assigned to the MPL5b biozone. A sample taken at the top of CST-3 yielded a foraminiferal assemblage characterized by the occurrence of B. marginata and G. inflata and the absence of Globorotalia truncatulimoides. Finally, samples collected from CST-4, CST-5, and CST-6, contain rather poor foraminiferal assemblages, which resemble those of CST-1 and CST-2, and are dominated by B. basispinosa and B. marginata, but do not bear age-diagnostic planktonic taxa. Within this chronological framework, bounding unconformities at the bases of the six sequences have been tentatively correlated with MIS 84–74 and, as a result, the exposed sections of the Monte Ascensione and Castignano systems overlap in the time range spanning the period between MIS 84 and MIS 77.

The vertical succession of depositional elements and bounding unconformities in the exposed portion of the Offida system can be resolved into five Motif-1 depositional sequences (Di Celma 2011). A single reversed-polarity interval encompasses both the highest part of hemipelagic mudstones of the canyon wall and the exposed section of the canyon fill from the base of O-1, up to the mud-prone interval of O-2. This is followed by a long interval of normal polarity comprising O-3, O-4, and O-5, spanning about 25 m of the immediately overlying hemipelagic mudstones. These, in turn, have a brief reversed-polarity interval in the upper part followed by a very short interval of normal polarity. In its uppermost portion, the long reversed-polarity interval is characterized by the occurrence of the calcareous nannofossils Discoaster brouweri and Discoaster triradiatus, and the planktonic foraminifera G. inflata, whereas the overlying normally magnetized interval is characterized by a foraminiferal assemblage indicative of the MPL6 biozone, lack of specimens belonging to the genus Discoaster, and occurrence of small Gephyrocapsa (Cantalamessa et al. 2009). These biostratigraphic constraints imply that the R−N−R−N polarity sequence recorded in these sediments can be readily correlated with the magnetic transition between the reverse-polarity Matuyama Chron and the Olduvai normal-polarity Subchron, the short reversed-polarity interval in the upper part of the Olduvai Subchron, which has an astronomically tuned age of 1.830–1.795 Ma in the Vrica stratotype section (Lourens et al. 2004), and the normal-polarity interval at the end of the Olduvai Subchron, respectively; the top of this normally magnetized interval (1.778 Ma) was not reached (Cantalamessa et al. 2009).

Collectively, these chronological constraints support an age-model where sequences O-1, and O-2, were deposited during the Matuyama Chron, immediately below the onset of the Olduvai Subchron, and their bases can be correlated with MIS 76–74.
The Colle Montarone system consists of a stack of seven deep-water depositional sequences (Di Celma et al. 2010). Mudstone samples for biostratigraphic analysis were collected from both the canyon fill and the encasing mud-rich hemipelagic strata. Samples taken from the northern wall of this canyon, which predate its incision, are characterized by the joint occurrence of *B. basispinosa* and *G. crassaformis* and the absence of *B. marginata*. Samples drawn from CM-12, CM-22, and CM-32 contain specimens of the benthic foraminifera *B. basispinosa* and *B. marginata*. These, coupled with the occurrence of a few specimens of the age-diagnostic foraminifera *Brizalina alata* and *G. inflata* within samples collected in CM-12, and the absence of *Bulimina elegans marginata*, suggest a possible latest Gelasian age for these strata. Samples drawn from CM-41, CM-51, CM-61, and CM-71 provided a rich fauna of age-diagnostic benthic foraminiferal species (*B. elegans marginata*) and nannofossils (small *Gephyrocapsa*). These data, associated with the absence of medium-sized *Gephyrocapsa* spp., point to deposition during the earliest Calabrian. Finally, a sample from the base of the thick succession of hemipelagic mudstones immediately above CM-71 records the last occurrence of the calcareous nannofossil *Calcidiscus macintyrei*, and its co-occurrence with medium *Gephyrocapsa* spp. and foraminifera *Globigerinoides tenellus* and *Bulimina etnea*. In summary, based on the tight chronostratigraphic control available, the lower three sequences were deposited between the first appearance of *B. alata* and that of *B.
**Discussion and conclusions.** Unlike continental shelves, where Pleistocene glacio-eustatic sea-level oscillations can be easily recognized in the form of shallow-water cyclothems, slope turbidite systems display a complex interplay of erosional and depositional processes and their stratigraphic records are traditionally depicted as fundamentally discontinuous and characterized by lithological patterns that are difficult to predict. However, a detailed chronostratigraphic framework, based on the combination of biostratigraphy, magnetostratigraphy and physical stratigraphy, has been constructed for the well-exposed Monte Ascione, Castignano, Offida and Colle Montarone strata and provides important constraints for stratigraphic correlation of the four successions into a composite record. Sedimentary facies analysis and recognition of unconformities within these slope successions reveal the occurrence of as many as 31 sequences that can be correlated with 24 cycles of the global oxygen isotope record for the time interval covered by MIS G2–60 (c. 2.65–1.7 Ma). The match between the sequences and the global oxygen isotope curve is unlikely to be fortuitous and provides reasonable evidence that the flux of terrigenous clastic sediment to the slope was regulated by recurring cycles of obliquity-driven (41 ka duration) sea-level change. Further support for the glacial eustatic origin of sequences is provided by the age of the onset of turbidite deposition into the Monte Ascione canyon, which started in the late Pliocene at c. 2.65 Ma, nearly coincident with the time proposed for the major intensification of Northern Hemisphere glaciation (e.g. Raymo 1994). As such, the studied turbidite successions are of compelling interest, as they (1) represent one of the most complete and well-constrained onland deep-water records of high-frequency, late Pliocene to early Pleistocene global sea-level fluctuations yet described and (2) afford an unprecedented opportunity to examine the sedimentary response to these recurring changes within depositional contexts usually considered unsuitable, such as slope systems.

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