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Echinoid assemblages from the early Miocene of Funtanazza (Sardinia): A tool for reconstructing depositional environments along a shelf gradient

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ABSTRACT

Lower Miocene echinoid assemblages from Funtanazza, midwestern Sardinia, are studied with respect to reconstructing palaeoenvironmental conditions along a shelf gradient. This is accomplished by 1) detailed logging of sedimentary facies, 2) applying functional morphological reconstructions of echinoid skeletons and interpreting their behaviour and life habits, 3) quantifying various taphonomic features of test preservation, and 4) analysing accompanying fauna and flora.

The Funtanazza section is dominated by fine- and coarse-grained siliciclastic lithologies. Eighteen genera of both regular and irregular sea urchins are recognized herein. Of these, sixteen occur in seven echinoid assemblages which were distinguished with respect to abundance, diversity, taphonomy and lithology. Littoral environments are characterized by the camarodonts *Genocidaris* and *Psammechinus*, the clypeasteroids *Clypeaster* and *Echinocyamus*, and the echinolampadoids *Hypsoclypus* and *Echinolampas*; the cidaroids *Prionocidaris* and *Tylocidaris* (*Sardocidaris*) and the spatangoid *Spatangus* are also present. Higher diversity is represented in inner sublittoral environments with the co-occurrence of the regular echinoids *Prionocidaris*, *Tylocidaris* (*Sardocidaris*), *Tripneustes* and *Genocidaris* and the irregular echinoids *Clypeaster*, *Echinocyamus*, *Hypsoclypus*, *Echinolampas*, *Schizaster*, *Spatangus*, *Lovenia* and *Trachypatagus*. Outer sublittoral environments are dominated by spatangoid echinoids and the cidaroid *Tretocidaris* (*Stylocidaris*).

Various substrates, such as boulders and pebbles, mobile fine and coarse sediments, secondary hardgrounds and seagrass and bryozoan patches, can be inferred. Preservation style with respect to abrasion, fragmentation and encrustation can vary widely among different taxa and environments and are interpreted as a function of constructional morphology and ambient environmental factors.

The echinoid assemblages of Funtanazza contain taxa which, in part, are widespread in the Miocene sedimentary successions of the circum-Mediterranean area. The described echinoids and assemblages are compared to other similar coeval occurrences and their applicability as palaeoenvironmental indices discussed.

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1. Introduction

Echinoids represent excellent tools for palaeoenvironmental reconstructions due to 1) their high preservation potentials as complete skeletons as well as fragments, 2) the fact that they occur in various sedimentary environments allowing reconstructions across facies boundaries, and 3) the possibility of applying functional morphology to their highly adapted skeletons to reconstruct life histories.

Echinoderms in general, with their variously constructed multiplated skeleton, are potentially good indicators of taphonomic processes and thus can reflect ambient ecological conditions (e.g. Lewis, 1980; Donovan, 1991; Gordon and Donovan, 1992; Brett et al., 1997; Ausich, 2001; Nebelsick, 2004). Actualistic studies based on laboratory and field observations have helped to clarify the taphonomic processes affecting echinoid skeletons after death (Allison, 1990; Kidwell and Baumiller, 1990; Greenstein, 1991, 1993a, 1993b, 1995; Nebelsick, 1992b, 1999, 2008; Nebelsick and Kampfer, 1994; Lewis et al., 2000; Schein and Lewis, 2000; Banno, 2008; Dynowski, 2012). These studies have shown that the preservation of echinoids is related to a complex interplay of factors such as constructional morphology including the architecture of test and nature of connective tissues, temperature, oxygen content, bacterial activity and transport mechanisms. Actualistic studies on their behaviour, ecological distribution and taphonomy allow for the palaeoenvironmental reconstruction especially for Cenozoic echinoids which are represented by the same or closely related taxa (Kroh and Nebelsick, 2010).

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Regular echinoids, particularly those with imbricate plates and abutting plates, such as echinothurioids, cidaroids, and diadematoids, dissociate rapidly after soft-tissue decay and have little chance of being preserved as complete tests (Kidwell and Baumiller, 1990; Greenstein, 1991). Smith (1984)suggests that the low preservation potential of regular echinoids is primarily related to the fact that they diversified as grazers on firm or rocky substrates in shallow-water environments that represent areas of active erosion. Although these areas often show higher echinoid diversity than soft substrates due to habitat differentiation, they are less conducive to preservation of fragile tests due to physical reworking and fragmentation (Nebelsick, 1996; Mancosu et al., 2015).

Skeletal architecture and environmental conditions are also important factors influencing the preservation potential of irregular echinoids (Kier, 1977; Smith, 1984; Greenstein, 1993b, 1995; Nebelsick, 1996). Clypeasteroids possess thick skeletons, a high degree of interlocking reinforced by calcareous struts penetrating into adjacent coronal plates, and internal supports that connect the oral and aboral sides of the test; they have a higher preservation potential than other irregular forms such as thin-plated spatangoids (Seilacher, 1979; Donovan, 1991; Nebelsick and Kroh, 2002; Belaústegui et al., 2012; Mancosu and Nebelsick, 2013). Experimental taphonomic investigations on clypeasteroid echinoids conducted by Nebelsick and Kampfer (1994) reveal that minute spines, which covered the whole test, were lost rapidly (within days) while most tests remained complete for longer periods of time. Plate disarticulation can be induced, however, by predation, scavenging and burrowing, and occurs rapidly after the structural integrity of the test is lost. In addition, irregular echinoids evolved and diversified as deposit feeders. They are often buried within unconsolidated substrates in areas of active sedimentation, such as sand and mud fields from shallow to deeper water environments. This leads to a better fossil record of irregular echinoids compared to that of regular sea urchins (Kier, 1977; Smith, 1984).

The test morphology of echinoids is determined by phylogenetic constraints and functional morphological adaptations to the specific environments in which these animals live (Smith, 1984, 2005). The detailed analysis of skeletal features such as test shape and architecture, spines and spine tubercles, ambulacral pore morphologies, the position of the peristome and periproct, jaw morphologies (if present) and others features can provide information for general habitats (such as the nature of the substratum and water turbulence), respiration, feeding mechanisms, locomotion, substrate relationships, burrowing depths of infaunal forms (Kier, 1972; Smith, 1978b; McNamara and Philip, 1980b; McNamara, 1987; Rose and Poddubiuk, 1987; Smith et al., 1995; Baumeister and Leinfelder, 1998; Néraudeau et al., 2001; Mitrović-Petrović, 2002; Kroh and Nebelsick, 2003).

Sardinia is well known for a rich echinoid fauna in the Miocene sediments from different depositional environments (e.g. Cotteau, 1895; Airaghi, 1905; Capeder, 1906; Lambert, 1907, 1909; Lovisato, 1911a, b, c, 1912a, b; Checchia-Rispoli, 1921; Di Giorgio, 1923; Comaschi Caria, 1955, 1963, 1972). More recently there have been a number of studies dealing with the sedimentological setting, taphonomy, and subsequent palaeoenvironmental interpretation of echinoids from different environmental settings from Sardinia (Mancosu and Nebelsick, 2013, 2015; Mancosu et al., 2015).

In this paper, a rich echinoid fauna from the historically well-known locality of Funtanazza (midwestern coast-line of Sardinia) is studied in detail with the aim of reconstructing the palaeoenvironment along a shelf gradient. This is accomplished by using sedimentological and taphonomic signatures, the functional morphology of echinoid tests as well as accompanying faunal and floral evidence. Although identification to species level was attempted whenever possible, a rigorous taxonomic revision of echinoid taxa at species level is beyond the scope of this study. A taxonomic study is ongoing and will be published elsewhere.

2. Geological setting

The Oligo-Miocene sedimentary succession in Sardinia consists of three sedimentary cycles that are mainly located within the NNW–SSE orientated Sardinian Basin, the origin of which is subject to debate (Fig. 1A) (Assorgia et al., 1997a; Cherchi and Montandert, 1982; Carmignani et al., 2001; Funedda et al., 2000; Lecca et al., 1997). The studied sedimentary sequence is present along the coast of Funtanazza, from the locality of Calada bianca to the beach of the Casa al mare F. Sartori, and is located within the so-called Funtanazza Graben, a E-W orientated tectonic basin (Fig. 1B) that, similar to the Sardinian Basin, originated during the rifting phase affecting the Western Mediterranean in the Oligocene to Aquitanian (Cherchi and Montandert, 1982; Assorgia et al., 1992, 1997a; Annino et al., 2000).

Within the Funtanazza Graben, a thick Oligo-Miocene volcano-sedimentary sequence is present (Fig. 1C); the sequence, which shows a wide range of both terrestrial and marine facies, has previously been described in detail by Assorgia et al. (1992) in which five informal lithostratigraphic units (Units A to E) are distinguished. The studied section belongs to Unit E of this succession. The sedimentary sequence unconformably overlies the igneous-metamorphic Palaeozoic Basement and starts with Late Oligocene continental polygenic conglomerates which pass upwards into lacustrine black to brown limestones containing gastropods and algal remains (Barca, 1974; Assorgia et al., 1992). These sediments are overlain by a fully marine deposit with abundant remains of the gastropod *Pereiraia gervaisi*, the shell of which is dated at 23.9 ± 0.3 Ma (Late Oligocene to Early Aquitanian) by using the $^{87}Sr/^{86}Sr$ ratio (Barbieri et al., 1997). This deposit is followed by a volcanic level, which is overlapped by a thick marine sequence, mainly characterized by siliciclastic sediments, with sporadic volcanic and lacustrine levels (Assorgia et al., 1997b). The succession ends with the subaerial calc-alkaline deposits from the Monte Arcuentu Volcanic complex, the activity of which ends with the intrusion of subvertical basaltic dikes that cut the sedimentary succession and whose ages as dated by the K–Ar method, range between 18.3 ± 1.5 and 16.7 ± 2 Ma (Assorgia et al., 1984; Brotzu et al., 1997).

The marine sedimentary sequence at Funtanazza, containing the echinoid assemblages studied here, is a ca. 80 m-thick siliciclastic succession (Fig. 2) and approximately corresponds to the section D-D' described by Assorgia et al. (1992). Radiometric dating using the $^{87}Sr/^{86}Sr$ ratio provided an age between 22.3 ± 0.3 Ma and 20.3 ± 0.2 Ma (Aquitanian to Early Burdigalian) for the succession (Barbieri et al., 1997). The sedimentary succession is highly fossiliferous with macrofossil content characterized by echinoids, molluscs, corals and bryozoans. The echinoids, which are widely distributed throughout the studied sedimentary sequence, have been described by Cotteau (1895); Lambert (1907, 1909); Lovisato (1911c); Comaschi Caria (1963, 1972); Stara and Borghi (2012) and Stara et al. (2016).

3. Material and methods

Palaeontological, taphonomic and sedimentological analyses were conducted in the field and laboratory. Numerous complete and fragmented echinoid tests are present and were systematically collected throughout the succession in 2014 and 2015. Taxonomic classification at and above genus level follows Kroh and Smith (2010) and Smith and Kroh (2011).The identification of well-preserved echinoid fragments was possible upon comparison with complete specimens. The taxonomic level to which the fragments can be identified depends on the presence and recognition of morphological characters (e.g. Nebelsick, 1992a, 1992b; Donovan, 2003). The abundance of echinoid fragments and complete tests per rock surface was estimated and the degree of close-packing determined by using the categories dense, loose, and dispersed following Kidwell and Holland (1991). Taphonomic signatures such as disarticulation, fragmentation, abrasion, encrustation and bioerosion were evaluated in the field using a hand lense and in

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