C. R. Geoscience 348 (2016) 150–157

Contents lists available at ScienceDirect

Comptes Rendus Geoscience

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Stratigraphy, Sedimentology

Influence of relative sea-level variations on the genesis of palaeoplacers, the examples of Sarrabus (Sardinia, Italy) and the Armorican Massif (western France)

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ARTICLE INFO

Article history:
Received 26 August 2015
Accepted after revision 23 September 2015
Available online 19 January 2016

Handled by Sylvie Bourquin

Keywords:
Heavy minerals
Gamma ray
Sequence stratigraphy
Ordovician
Sea-level changes
Condensation

ABSTRACT

The aim of this work is to analyse the role of allocyclic processes in the genesis of marine Ordovician palaeoplacers laid down on a terrigenous shelf dominated by storm waves. Sedimentological (facies, sequence stratigraphy) and petrographic analyses combined with natural radioactivity measurement (gamma ray) are carried out. Two facies containing heavy minerals are identified: a shoreface facies and a proximal upper offshore facies. Heavy minerals (mainly titaniferous minerals, zircon and monazite) are concentrated in laminae that can amalgamate to form placers that are several decimetres thick. Their occurrence is highlighted by an increase in the total radioactivity (up to 140,000 cpm) and in the U and Th contents (up to 130 ppm and 800 ppm, respectively). The palaeoplacers are the result of a combination of autocyclic and allocyclic factors. In the stratigraphic record, the palaeoplacers are located in the retrogradation phases and express condensation processes in the nearshore environments.

1. Introduction

Heavy mineral-rich laminae (HMRL) occur in many sedimentary environments from continental settings (fluvial: e.g., Carling and Breakspear, 2006; eolian: e.g., Sawakuchi et al., 2009) to nearshore environments (e.g., Babu et al., 2007; Dillenburg et al., 2004; MacDonald and Rozendaal, 1995). They are generated by instantaneous hydraulic or aerodynamic processes such as selective grain entrainment and transport, or shear sorting (e.g., Hughes et al., 2000; Komar and Wang, 1984; Slingerland, 1977). HMRL are either scattered or form thick horizons (from a few centimetres to several metres thick) that are of potential economic interest (placer). Pleistocene and Holocene marine placers have been the subject of numerous studies and the influence of sea-level variations has been mentioned in some of these works (e.g., Dinis and Soares, 2007; Roy and Whitehouse, 2003; Roy et al., 2000; Sawakuchi et al., 2009); however, little attention has been paid to the position of palaeoplacers in the stratigraphic record. The aim of this work is to analyse the role of allocyclic processes in the genesis of some marine Ordovician (lower Palaeozoic) palaeoplacers. This study was carried out in terrigenous successions located in two regions of the North Gondwana domain (Fig. 1): the Sarrabus area (Punta Serpeddì Formation) in Sardinia (Italy), and the Crozon Peninsula (Grès Armoricain and Postolonnec formations) in the Armorican Massif (western France).

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http://dx.doi.org/10.1016/j.crte.2015.09.006

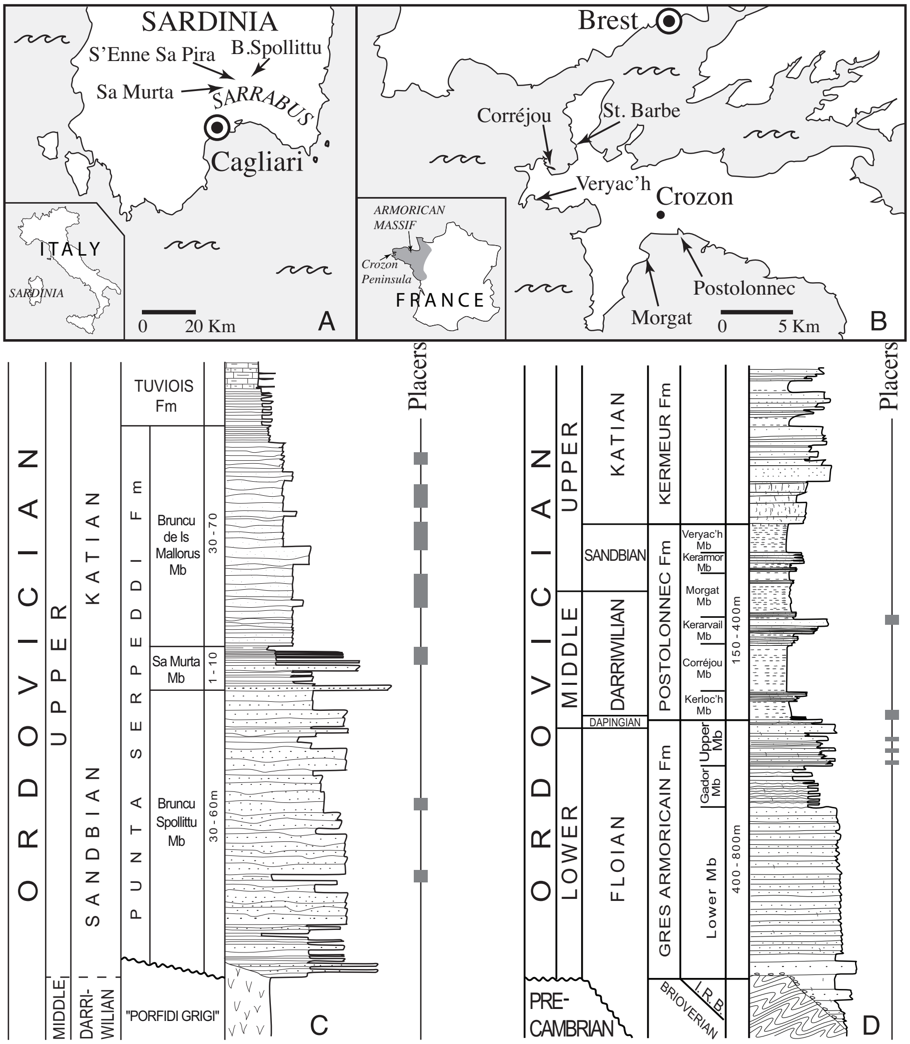

Fig. 1. Location and lithologic columns of the studied sections in the Sarrabus area (A, C) and in the Crozon Peninsula (B, D).

2. Geological setting

In the Sarrabus area (Fig. 1A, C), the Punta Serpeddì Formation (Fm), Sandbian–Katian in age, rests on the "Porfidi Grigi" volcanic rocks that were emplaced in a magmatic arc setting (Darriwilian to Sandbian: Oggiano et al., 2010; Pavanetto et al., 2012a, 2012b). The sedimentary succession is deposited in a post-arc rift context (Gaggero et al., 2012) and is overlain by the Tuviois Fm (Katian–Hirnantian?). The Punta Serpeddì Fm (60 to 140 m thick) consists of fine- to coarse-grained lithic wackes containing intercalations of conglomerates, microconglomerates, and siltstones. It is subdivided into three members; HMRL are abundant in the Sa Murta and Bruncu de Is Mallorus members (Loi and Dabard, 1997; Loi et al., 1992) and are scattered in the Bruncu Spollittu Member (Mb). Three stratigraphic sections have been studied (Pistis, 2009); however, only the most complete one (the S'Enne Sa Pira section) is presented here.

In the Crozon Peninsula (Fig. 1B, D), the Grès Armoricain Fm (Floian–Dapingian) rests either unconformably on the Brioverian strata (upper Proterozoic to lower Cambrian) or conformably on the Initial Red Beds (Floian). It consists of fine- to coarse-grained quartzarenite and quartzwacke beds with some intercalations of clayey siltstone. It is subdivided into three members and the placers are mainly located within the Upper Mb (Faure, 1978; Noblet, 1984). The overlying Postolonnec Fm (Dapingian to Sandbian) consists of four clayey-silty members containing subordinate sandy intercalations and two sandy members (Kerarvail and Kerarmor members); the HMRL are located at the base of the formation (Kerloc'h Mb) and in the uppermost part of the Kerarvail Mb. After a major sea-level fall, the Postolonnec Fm is overlain by the transgressive Katian Kermeur Fm (Vidal et al., 2011). Five stratigraphic sections have been studied (Pistis, 2009); however, only the Morgat and Postolonnec sections are presented here.

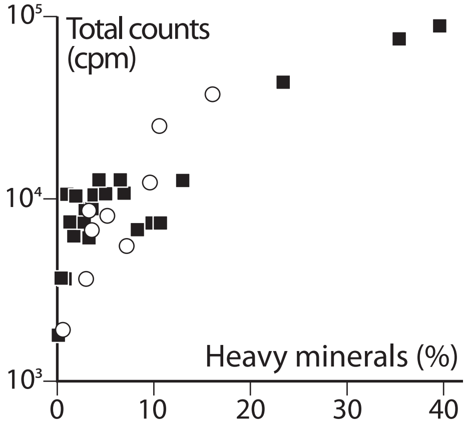

Fig. 2. Heavy minerals contents (%) versus gamma ray total counts (counts per minute) in sandstones from the Armorican Massif (squares) and Sarrabus (circles).

3. Methods

A sequence analysis based on detailed logs (1:50 scale) was carried out following the integrated approach of genetic stratigraphy: based on the facies analysis and the interpretation of the depositional environments, genetic units were identified and the stacking pattern of these units was established (see Loi et al., 2010).

Petrographic analyses coupled with modal analyses (1000 points per thin section, in direction orthogonal to the lamination) were performed in intervals containing HMRL. In sediments, radioactivity is mainly linked to heavy minerals containing U and Th, and to potassic clay and feldspars. Highly radioactive minerals, such as zircon and monazite, are present in the studied sections and the total radioactivity (total counts per minute) is positively correlated (Fig. 2) with the relative abundance of heavy minerals (Pistis et al., 2008). Natural radioactivity was thus measured along the sedimentary successions using a portable spectrometer RS-230 (Radiation Solutions, Inc., Canada). Measurements were taken with a counting time of 120 s and a stratigraphic interval varying between 10 and 50 cm. The counts per minute (cpm) in the selected windows were converted into K (%), U (ppm) and Th (ppm) concentrations.

4. Depositional environments and sequence analysis

Facies occurring in the studied successions have been formerly documented (Botquelen et al., 2004, 2006; Dabard and Loi, 2012; Dabard et al., 2007; Durand, 1985; Loi and Dabard, 2002; Loi et al., 1999). Sandy facies are characterised by the occurrence of sedimentary structures, i.e. hummocky cross-stratification (HCS), swaley cross-stratification (SCS), planar or gently inclined lamination and graded rhythmites, which indicate depositional environments dominated by storm wave action. They are interbedded with silty to clayey facies containing, in some places, facies generated by condensation/diagenetic processes (e.g., siliceous and phosphatic concretions, shellbeds).

In the Sarrabus area (Fig. 3), the Bruncu Spollittu and Sa Murta members were laid down in a nearshore environment (restricted marine to shoreface settings); a deepening trend toward the distal upper offshore is recorded from the Sa Murta Mb (Loi et al., 1992). The

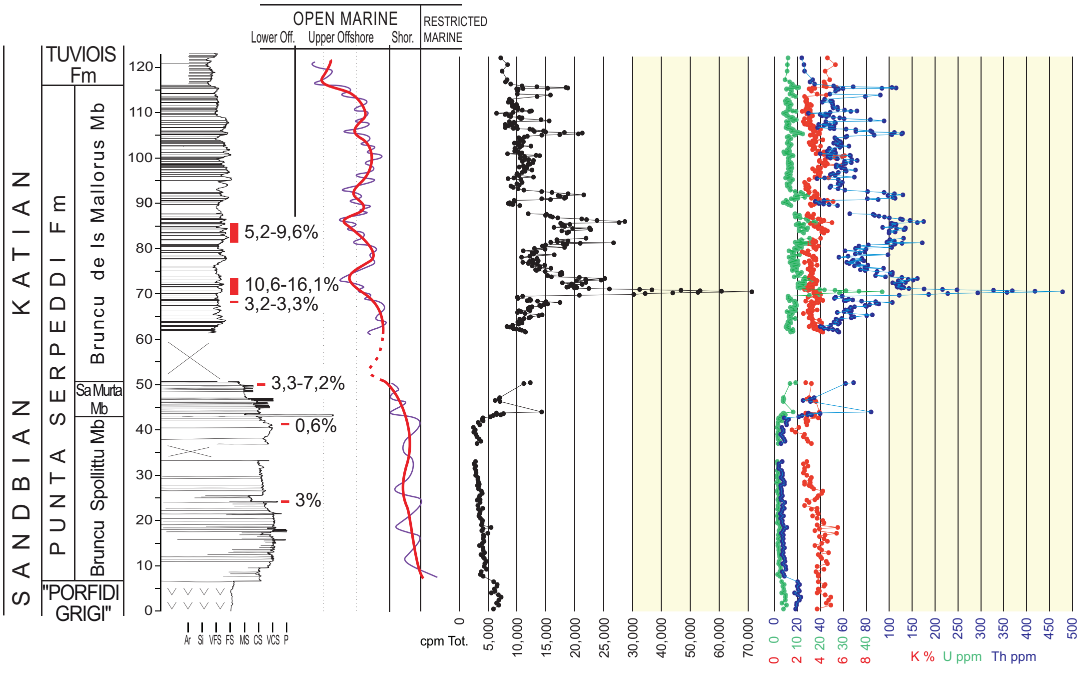

Fig. 3. Vertical evolution of the sedimentary environments of the Puna Serpeddì Fm (S'Enne Sa Pira section). Heavy mineral contents of samples from different sections (vertical red lines); gamma ray spectral logs: total counts (cpm), K (%), U (ppm) and Th (ppm).

stacking pattern of the facies along the Punta Serpeddì Fm therefore attests to a major retrogradation phase (Loi et al., 1992) known as the "Caradocian transgression Auct". This deepening coincides with a significant increase in the total radioactivity with increases in the U and Th contents.

In the Armorican Massif (Fig. 4), the combined influence of tides and storms controlled the deposition of the Gador and Upper members of the Grès Armoricain Fm (Dabard et al., 2007; Durand, 1985). Sediments were laid down between the nearshore (restricted marine and shoreface settings) and the proximal upper offshore, and at least three retrogradation phases are recorded. The transition to the base of the Postolonnec Fm (Fig. 5) is linked to a significant deepening toward the lower offshore. Then, several progradation–retrogradation cycles followed, with environment shifts restricted to the offshore (Dabard et al., 2015). At the transition between the Kerarvail and the Morgat members, a new deepening episode from the shoreface to the lower offshore is recorded. Later, this was followed by minor environmental variations limited to the lower offshore and the distal upper offshore. In the two Armorican formations, the retrogradation phases toward the shoreface or proximal upper offshore coincide with a significant increase in the total radioactivity and in the U and Th contents (Figs. 4 and 5).

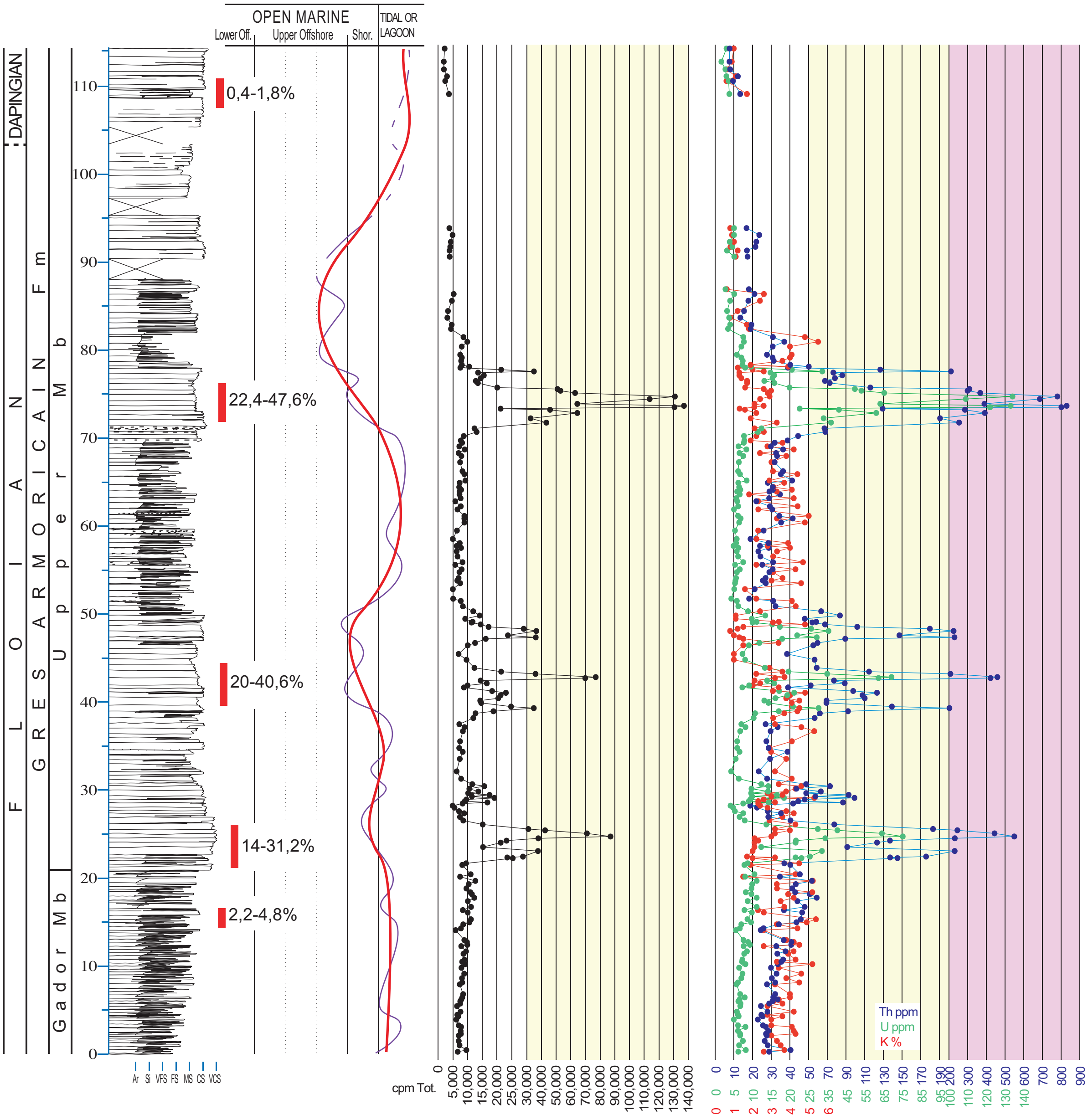

Fig. 4. Vertical evolution of the sedimentary environments of the Gador and Upper members of the Grès Armoricain Fm (Morgat section). Heavy minerals contents (vertical red lines); gamma ray spectral logs: total counts (cpm), K (%), U (ppm) and Th (ppm).

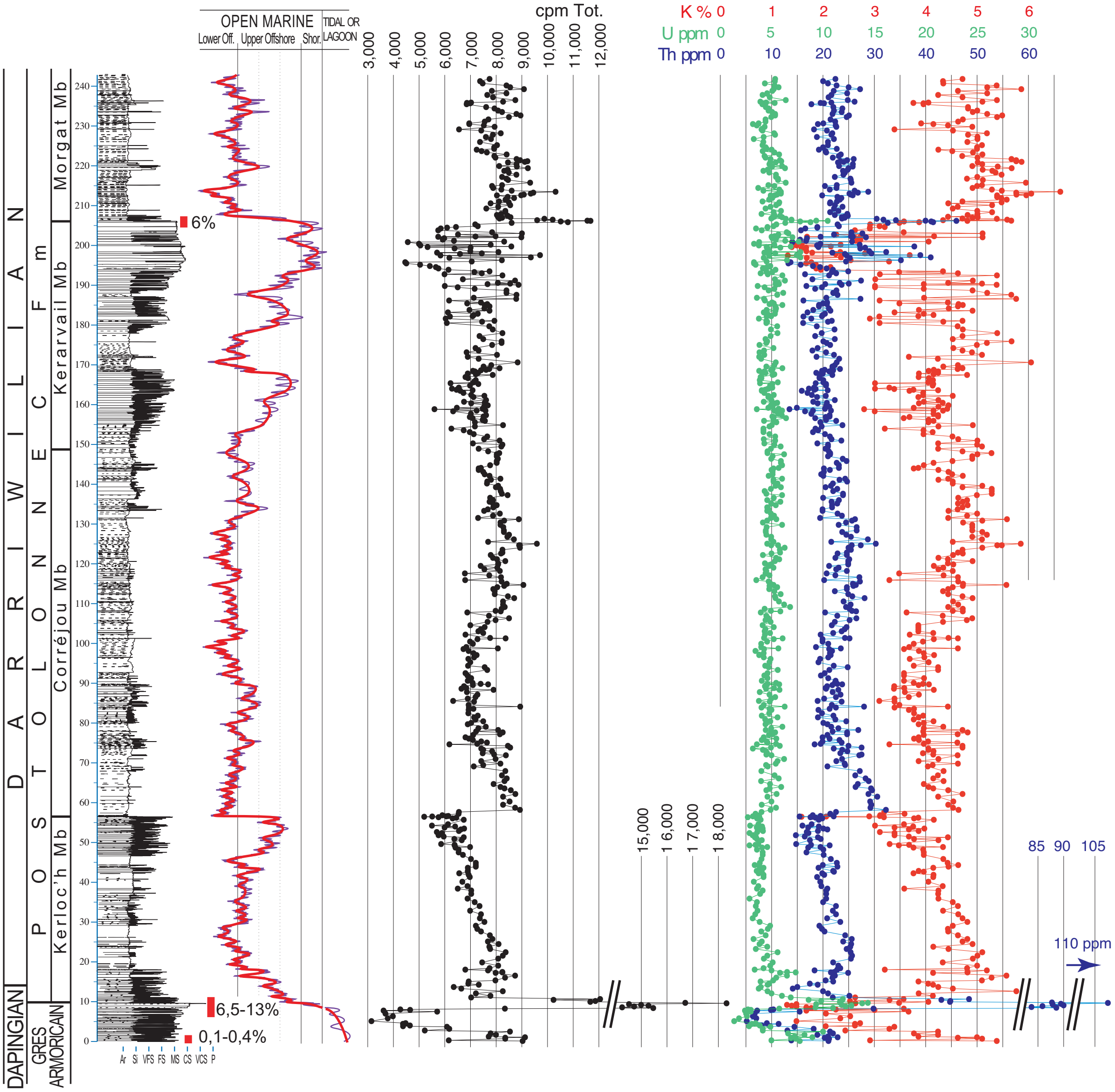

Fig. 5. Vertical evolution of the sedimentary environments of the basal members of the Postolonnec Fm (from Dabard et al., 2015). Heavy minerals contents (vertical red lines); gamma ray spectral logs: total counts (cpm), K (%), U (ppm) and Th (ppm).

5. Description of the placer deposits

Placers occur in two sedimentary facies. The first one (Fig. 6A and B) consists of coarse-grained sand strata (0.2 m to 2 m thick), showing SCS, planar or gently inclined laminations and cross-laminations; it was laid down on the shoreface. Heavy minerals are concentrated in laminae up to 1 mm thick, alternating with quartz laminae. HMRL can amalgamate to form placer deposits that are several decimetres thick (Fig. 6A). This facies occurs in the Bruncu Spollittu Mb (Punta Serpeddì Fm), at the topmost part of the Gador Mb and in the Upper Mb of the Grès Armoricain Fm, and at the top of the Kerarvail Mb (Postolonnec Fm). The second facies is made up of fine-grained sand strata (1 to several decimetres thick) with HCS; it was deposited in the proximal upper offshore (Fig. 6C and D). Heavy minerals form dark and yellow-brown laminae that highlight HCS and alternate with quartz laminae containing some scattered heavy minerals. This facies occurs in the Bruncu de Is Mallorus Mb (Punta Serpeddì Fm) and at the base of the Postolonnec Fm.

In the Punta Serpeddì Fm, heavy minerals can account for more than 16% of the clastic components (Fig. 3). Assemblages are mainly made up of rutile, pseudo-rutile, anatase, zircon and monazite; tourmaline, xenotime, ilmenite and opaque minerals are less abundant. The grain size varies with the species: titaniferous minerals can reach 300 μm, zircon and tourmaline are roughly 100 μm in size and monazite is always smaller than 60 μm. A mineralogical segregation of the heavy minerals according

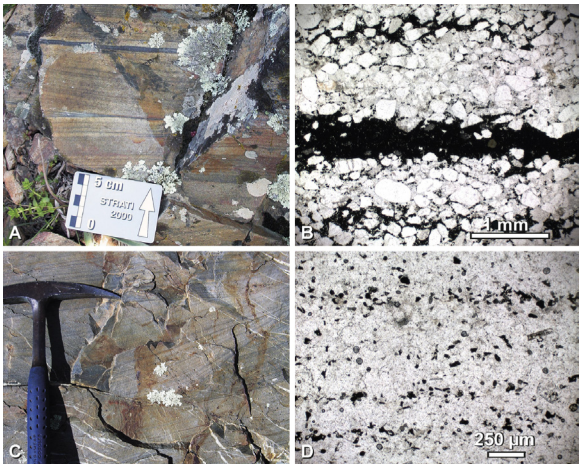

Fig. 6. Heavy mineral laminations, in the shoreface facies with planar and gently inclined laminations (A, B) and in the proximal upper offshore with hummocky cross-stratification facies (C, D).

to the host-sediment granulometry is observed. In the coarse-grained facies of the shoreface, HMRL are enriched with titaniferous minerals (represented by TiO_2 in Fig. 7), while in the fine-grained facies of the upper offshore, zircon and primarily monazite (represented by Zr and Ce + La, respectively, in Fig. 7) are more abundant. This mineralogical segregation explains the natural radioactivity variations between the different facies. In the coarse-grained sands of the Bruncu Spollittu Mb, the total radioactivity is relatively low (ca. 5000 cpm) even in the HMRL (e.g., approximately 25 m in Fig. 3); this feature can be explained by the abundance of titaniferous minerals. In the fine-grained sands of the Sa Murta and Bruncu de Is Mallorus members, the radioactivity increases (up to 71,000 cpm) with high U and Th contents (up to 46 ppm and 450 ppm, respectively) in the placers due to the abundance of zircon and monazite.

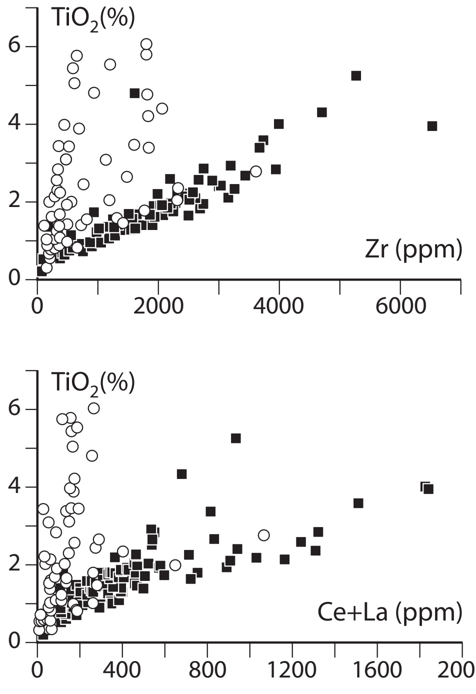

Fig. 7. TiO_2 (%), Zr (ppm) and Ce + La (ppm) distributions in coarse (circles) and fine (squares) sands from the Punta Serpeddì Fm.

In several placers of the Armorican succession, heavy minerals are very abundant and can reach more than 40% of the clastic components (e.g., Upper Mb of the Grès Armoricain Fm, Fig. 4). HMRL are mainly made up of titaniferous minerals (rutile, anatase, brookite, leucoxene) that represent more than 70% of the whole heavy minerals content; zircon, monazite and tourmaline are less abundant. Other heavy particles are present, such as Lingula shell fragments in the Grès Armoricain Fm and phosphatic and siderite clasts at the base of the Postolonnec Fm (Dabard et al., 2007). The grain size of heavy minerals species varies little, between 50 and 120 µm. The distribution of the placers is perfectly shown by the natural radioactivity. Several radioactivity peaks are present, especially in the Grès Armoricain Fm where a radiation level higher than 70,000 cpm was measured (up to 140,000 cpm at about 75 m in Fig. 4) with very high Th and U contents up to 800 ppm and 130 ppm, respectively. At the base of the Postolonnec Fm (Fig. 5), the total radioactivity peaks of HMRL reach 18,000 cpm with Th and U contents up to 110 ppm and 13 ppm, respectively. The total radioactivity is lower in the Kerarvail Mb, with a value of approximately 11,500 cpm and Th and U contents of 45 ppm and 11 ppm, respectively.

6. Discussion

Instantaneous autocyclic processes can produce heavy mineral segregation in high-energy environments, but placers are not present in all of the shoreface and proximal upper offshore deposits. These features indicate that other factors, such as the renewal of source areas or the modulation of the volumes of the siliciclastic supply, must be invoked to explain their stratigraphic distribution.

In Sardinia, the source areas of the Punta Serpeddì Fm are constant throughout the succession and are mainly represented by the underlying volcanic rocks of the “Porfidi Grigi”, and, to a lesser extent, by the Cambro-Ordovician sediments of the “Arenarie di San Vito” and some Precambrian cratonic and metamorphic complexes (Dabard et al., 1994; Loi and Dabard, 1997; Loi et al., 1992). In the Armorican Massif, the Panafrican craton is likely the main source area for the Palaeozoic sediments, and, in any case, the fluctuations in the concentrations of the heavy minerals observed particularly in the Grès Armoricain Fm occur at much faster rates (high-frequency cycles) than the rate of renewal of the source areas. Therefore, the occurrence of placers is not linked to the renewal of source areas but can be explained by recurrent heavy mineral enrichment processes.

Our study shows that the placers are preferentially associated with episodes of relative sea-level rise, suggesting a combined influence of short-term autocyclic factors and long-term allocyclic factors (i.e. relative sea-level changes). During a relative sea-level cycle, “sediment

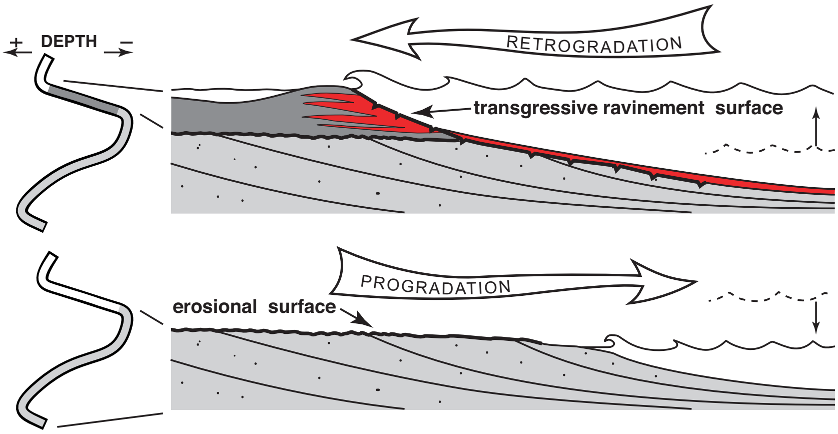

Fig. 8. Sketch diagram illustrating the placer deposits during relative sea-level variations. During the progradation phase, the heavy minerals are scattered in sediments. During the retrogradation phase, the sediments are stored in the coastal plain leading to a starvation of terrigenous inputs in marine environments and heavy minerals concentration (in red).

volume partitioning" (Cross and Lessenger, 1998; Gardner et al., 2004) leads to fluctuations in terrigenous inputs along the depositional profile. During periods of progradation (Fig. 8), the siliciclastic supply is abundant in marine settings. On the shoreface, a daily segregation of high-density particles occurs, but continuous supplies of sand result in dilution and do not favour the formation of placers. On the contrary, during periods of retrogradation, the preferential storage of sediments on the continent and the coastal plain leads to a relative starvation of the siliciclastic supply in the marine areas. On the shoreface, segregation processes affect a sandy stock that is weakly fed. These conditions allow for a progressive enrichment in heavy minerals via the winnowing of fine and light particles and the genesis of HMRL on the shoreface. These deposits can then be reworked by the storm waves and can supply the sandy strata of the upper offshore. Only the finer sand is removed during the reworking, resulting in a granulometric segregation in the assemblage of heavy minerals. Thus, in the Punta Serpeddì Fm, the coarse titaniferous grains stay in the shoreface and the HCS sandy strata of upper offshore are enriched with zircon and monazite.

The placers are formed during the retrogradation and aggradation phases when the sandy bodies of the shoreface progressively move landward on the coastal plain deposits, along the transgressive ravinement surface. Morphological conditions play an important role in the enrichment with heavy minerals. During the retrogradation phases, a weak coastal plain slope favours a lagoon-barrier system (e.g., Beets et al., 2003; Dillenburg et al., 2004). In these conditions, accommodation is important in the coastal plain where the sediments are trapped, which limits sedimentary inputs toward the shoreface. Marine deposits are then condensed and placers are the expression of condensation in nearshore environments.

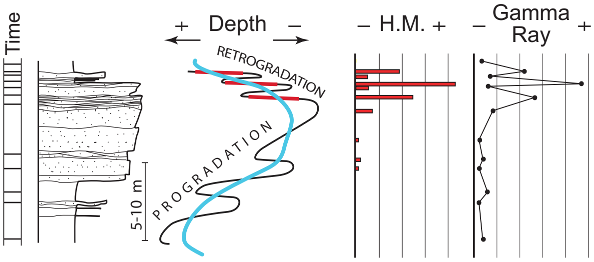

Fig. 9. Stratigraphic response to the superposition of sea-level cycles of different frequencies. The very high-frequency sequences located in the retrogradation phase are amalgamated and enriched with heavy minerals (H.M.) (in red).

The superposition of several sea-level cycles of different frequencies (e.g., Milankovitch cycles) can enhance the process (Fig. 9). Indeed, the higher frequency sequences, located in the progradation phase of the lower frequency sequences, have a higher supply than those located in the retrogradation phase. The sequences located in the retrogradation phase are thinner and are amalgamated, resulting in a long-term heavy mineral concentration through the continuous reworking and the mineralogical and granulometric segregation of the same sandy stock.

7. Conclusion

The studied placers are the result of a combination of autocyclic factors (e.g., shear sorting) and allocyclic factors (sea-level changes and sediment supply variations). They are produced during phases of retrogradation in shoreface and proximal upper offshore environments and represent condensation facies. These placers can be used to establish isochrones surfaces for intrabasinal correlations over a wide geographical area and especially for stratigraphic reconstructions in the geological mapping of metamorphic and/or deformed marine successions. In monotonous sandy successions, the distribution of palaeoplacers is a tool to identify genetic units and in well-log gamma ray analyses they are used to distinguish certain retrogradational sandy facies, with placers, from certain progradational sandy facies, without placers. Finally, in geological exploration, the understanding of the autocyclic and allocyclic processes responsible for the formation of placers provides a useful predictive tool for heavy mineral prospecting.

Acknowledgements

The authors acknowledge financial support from the grant "Legge Regionale 7 progetto annualità 2010" of "Regione Autonoma Sardegna" (resp. Alfredo Loi) and from the French "Agence nationale de la recherche" through grant ANR-12-BS06-0014 'SEQSTRAT-ICE'. The English version of the manuscript was post-edited by S. Mullin. The authors thank Dr. S.R. Dillenburg, Dr. P. Razin and Dr. G. Oggiano for comments and suggestions on the previous version.

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