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Geomaterials (Sedimentology)

New stratigraphic and sedimentological investigations on the Middle Eocene–Early Miocene continental successions in southwestern Sardinia (Italy): Paleogeographic and geodynamic implications

Nouvelles recherches stratigraphiques et sédimentologiques sur les successions continentales de l'Eocène moyen–Miocène inférieur du Sud-Ouest de la Sardaigne (Italie) : conséquences géodynamiques et paléogéographiques

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ABSTRACT

In SW Sardinia, the continental Tertiary successions referred up to now to the Cixerri Fm. (Middle Eocene–Lower Oligocene?) have been investigated. Sedimentological analysis suggests these deposits lied down in fluvial environments and comprised between distal braided streams passing eastward to meandering streams/coastal environments (?) under sub-arid climates. The scrutinization of the Cixerri Fm. westernmost successions allowed one to split locally the upper from the lower part based on sedimentological and mineralogical features and indirect dating. Unfortunately, this separation cannot be set everywhere. The few upper outcrops plainly evidenced and well-constrained have been newly named Flumentepido Fm. and assigned to Late Oligocene–Early Miocene: they figure out alluvial fans and proximal braided rivers. This way, the SW Sardinia Tertiary continental sedimentation extends its persistence, contemporaneously changing its tectostratigraphic meaning: from a molassoid context related to the Pyrenean wedge dismantling (Eocene–Oligocene) to a rift-margin succession connected with the opening of the Algero-Provençal back-arc basin due to the Apennine subduction in Oligocene–Miocene times.

RÉSUMÉ

Dans la Sardaigne du Sud-Ouest, de nouvelles analyses stratigraphiques et sédimentologiques des dépôts continentaux tertiaires de différents milieux fluviatiles, jusqu'à présent compris dans la Fm. du Cixerri (Eocène moyen–Oligocène inférieur ?), ont permis de séparer une unité inférieure, la *Fm. du Cixerri s.s.* (allant d'un faciès de fleuve sableux en tresse à celui de fleuves à méandres/environnement côtier ?), d'âge Eocène moyen à Oligocène inférieur, d'une unité supérieure, appelée dans cette note *Fm. de Flumentepido* (déposée en milieu de cone alluvial et de fleuve graveleux en tresse), d'âge Oligocène supérieur à Miocène inférieur. Ainsi, la sédimentation détritique terrigène, dans cette région, persiste entre l'Eocène moyen et le Miocène inférieur. Sa signification

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tectostratigraphique change dans le temps : elle passe d'un contexte de type molassique lié à l'érosion de l'orogène pyrénéen (Eocène–Oligocène), à un faciès de marge de rift lié à l'évolution du bassin d'arrière-arc algéro-provençal et à la subduction des Apennins.

1. Introduction

The Cixerri Fm. (Pecorini and Pomesano Cherchi, 1969) is a terrigenous continental unit of siltites, sandstones and subordinated conglomerates (Barca et al., 1973; Barca and Palmerini, 1973): often, at its base thin carbonate lacustrine lenses with characeae algae appear (Agus and Pecorini, 1977; Pala et al., 1977). Until now the unit has referred to a Middle Eocene–Early Oligocene? age (Agus and Pecorini, 1977; Pecorini and Pomesano Cherchi, 1969; Pittau Demelia, 1979). The Cixerri Fm. is widespread in the western (Sulcis-Iglesiente) and, at a lesser extent, in the central part of southern Sardinia (Trexenta) (Fig. 1, right). It mainly crops out in the morphostructural lows as are the southern Sardinia basin (Trexenta area), the Cixerri basin in between the Iglesiente and Sulcis, the Giba basin in the Sulcis, and the eastern "Lignitifero" basin bordering the Sulcis coast (Fig. 1, right). These basins were initiated by Late Oligocene–Lower Miocene extensional movements of the Sardinian Rift (Casula et al., 2001; Cherchi et al., 2008; Cherchi and Montadert, 1982). The Sardinian Rift is a meridian tectonic structure crossing all the island and forming the southern end of the European Cenozoic Rift System (Cherchi and Montadert, 1982; Dezés et al., 2004; Stampfli et al., 2002). So, in SW Sardinia the Cixerri Fm. is almost completely surrounded by structural highs uplifted by Tertiary extensional tectonics. Those highs are of Early Cambrian to Early Carboniferous metasediments and Permo-Carboniferous granitoids pertaining to the Variscan Chain [(Carmignani et al., 1994) and references therein]. The Cixerri Fm. is considered to be a molassoid unit (Barca and Costamagna, 2000; Cherchi, 1979), the deposits of which being mainly related to the dismantling of the southeastern part of the Cantabric-Pyrenean-Provençal Chain (northern Spain) [(Banda and Wickam, 1986) and references therein]. The last outskirts of this chain are located sparsely in SW (Sulcis) and NW (Nurra) Sardinia (Barca and Costamagna, 1997a; Barca and Costamagna, 2000). A possible alternative pertinence of the Eocene Sardinian tectonic deformations to the southeastern prosecution of the thrusts front of the Iberian Range has been proposed (Stampfli et al., 2002).

The Cixerri Fm. can be compared for tectosedimentary features and age with the Cuccur'E Flores Conglomerates (Barca and Costamagna, 2000) of Middle Eocene age (Lutetian) (Dieni et al., 2008), outcropping in NE Sardinia (Carmignani et al., 1992): here this unit most likely represents the local tectonic response to the "Pyrenean" deformations (Barca and Costamagna, 2000; Zattin et al., 2008). Moving to north, also the fluviatile Chiappa Conglomerates of probable Eocene age (Durand-Delga and Peybernés, 1986) outcropping close to Porto-Vecchio in the SE Corsica could be a comparable tectonofacies.

The Cixerri Fm. (Fig. 1, top left) posed above the "Lignitifero" succession, having an age of Latest Paleocene to Middle Eocene (Barca and Costamagna, 2000; Cherchi, 1979; Cocozza et al., 1989; Cocozza et al., 1974; Dreesen et al., 1997; Fanni et al., 1982; Murru and Salvadori, 1987; Pittau, 1974). The boundary between these two units is different depending to the locality: it varies from paraconformable to angular unconformable. Nonetheless, in some locality a sort of stratigraphic continuity could exist. The "Lignitifero" succession variously implicated deformations in the Pyrenean Phase. It is an informal, composite stratigraphic unit made up by different lithological subunits. Discontinuous continental, immature siliciclastics form the base (Arenarie di Monte Margiani Fm., 0–40 m thick) (Barca and Costamagna, 1997a; Barca and Costamagna, 1997b; Barca and Costamagna, 2000), related to weak tectonics (Laramic phase?) (Barca and Costamagna, 1997a; Barca and Costamagna, 1997b; Barca and Costamagna, 2000) during Latest Cretaceous to Early Paleogene times. These siliciclastics are followed by the marine Miliolitico limestones (30–40 m) and finally by the Lignitifero *s.s.* mixed siliciclastic to carbonate paralic succession with lignite layers at the top (110 m). This succession represents the tecto-sedimentary transgressive-regressive Pyrenean cycle (Barca and Costamagna, 2000) partially involved in the Pyrenean east-verging thrusts of the Alpine phase (Barca and Costamagna, 1997a; Barca and Costamagna, 2000; Carmignani et al., 2004).

A drilling campaign by Carbosulcis S.p.A. devoted to the exploitation of the coal seams contained in the "Lignitifero" (Assorgia et al., 1992a; Assorgia et al., 1992b) evidenced in the eastern "Lignitifero" basin bordering the Sulcis coast (Fig. 1, right), the Cixerri Fm. has a thickness of 210 to 320 m. Also some scattered drills for water research run in the Cixerri plain (Pala et al., 1977) measured a thickness ranging 100 to 300 m of the Cixerri Fm. Close to the SW Sardinia coast (Pula), the interpretation of seismic profiles (Casula et al., 2001) refers to the Cixerri Fm. an approximate thickness of 200 m.

The Cixerri Fm. is basically devoid of fossils: nevertheless, the age of its base is well defined by palaeontological data [Lutetian, Middle Eocene: Characeae algae (Agus and Pecorini, 1977); microflores assemblages (Pittau Demelia, 1979)]. In the centre of the unit (Flumentepido, Carbonia), a turtle shell (*Erymnochelys*, Eocene: discovery of S. Barca and A. Assorgia) (Righi and Delfino, 2003) occurred. Close to Villamassargia (Iglesias), the finding of an isolated specimen of gastropoda (*Lymnaea* cf. *orelongo* Bourée, Oligocene) (Maxia, 1959) suggests the upper part of the formation crops out here. Finally, poorly preserved samples of Cerithida, Ostreidae, Miliolida, *Planorbis* and *Gaudrina pseudocollinsi* contained in thin limestone layers of possible lacustrine origin have been found close to Monastir (southern Sardinia basin, Trexenta) (Pecorini and Pomesano Cherchi, 1969). The top of the unit is terminated by superimposed calc-alkaline volcanites of Late Oligocene–Early Miocene age (Assorgia et al., 1992a). The start

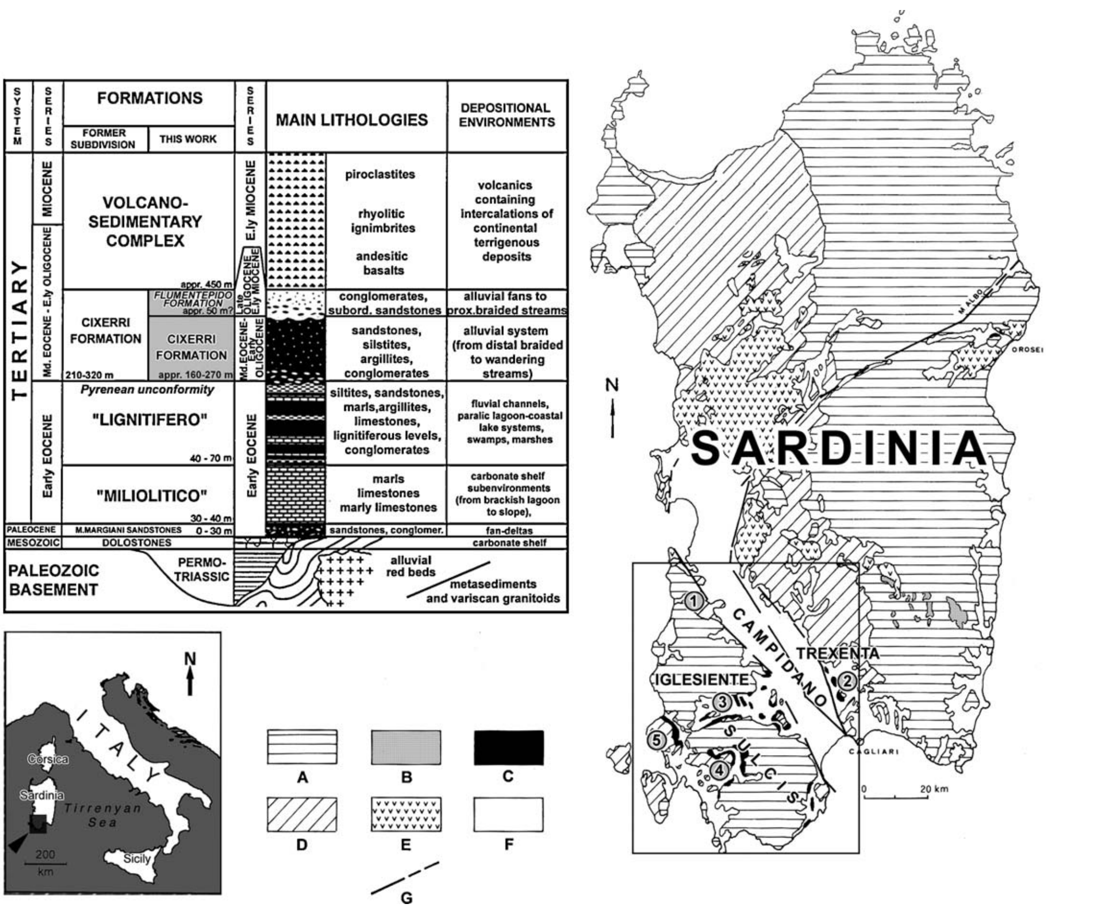

Fig. 1. Top left: stratigraphic scheme of the Tertiary succession of SW Sardinia. Bottom left: localization of the studied area. Right: geological sketch map of Sardinia. The continental Cixerri and Flumentepido Fms. are evidenced; A) Paleozoic Variscan basement and Permian to Cretaceous deposits; B) Lignitifero Group and M. Cardiga Fm. (Paleocene–Early Eocene); C) Cixerri and Flumentepido Fms. (Middle Eocene–Early Miocene); D) Other volcanic and sedimentary deposits (Oligocene–Miocene); E) Volcanics (Plio-Quaternary); F) alluvial sediments (Quaternary); G) Faults. 1) Funtanazza basin; 2) southern Sardinia basin: Trexenta; 3) Cixerri basin; 4) Giba basin; 5) Eastern "Lignitifero" basin.

Fig. 1. En haut à gauche : schéma stratigraphique de la succession tertiaire de la Sardaigne sud-occidentale. En bas à gauche : localisation de l'aire étudiée. À droite : carte géologique schématique de la Sardaigne. En évidence, les affleurements des deux formations du Cixerri et de Flumentepido. A) Socle varisique et couvertures permiennes à crétacées ; B) Groupe du « Lignitifero » et Fm. de Monte Cardiga (Paléocène–Eocène inférieur) ; C) Fms. du Cixerri et de Flumentepido (Eocène moyen–Miocène inférieur) ; D) Autres dépôts sédimentaires et volcaniques (Oligocène supérieur–Miocène inférieur) ; E) Volcanites plio-quaternaires ; F) Sédiments alluviaux quaternaires ; G) Failles. 1) Bassin de Funtanazza ; 2) Bassin de la Sardaigne méridionale (Trexenta) ; 3) Bassin du Cixerri ; 4) Bassin de Giba ; 5) Bassin oriental du « Lignitifero ».

of this volcanic cycle has been supposed between 32 Ma (Beccaluva et al., 1985) and 28 Ma (Lecca et al., 1997): we consider more plausible this later age, since it fits well with the oldest data coming from several dacitic intrusions [(Lecca et al., 1997) and references therein]. These volcanics related to the subduction of the Apulia plate under the European plate, to which the Sardinia-Corsica block still was connected. So, the top of the Cixerri Fm. has been assigned doubtfully to Early Oligocene.

2. Stratigraphic and sedimentological data

All available outcrops of the Cixerri Fm. in southern Sardinia have been considered and analyzed in order to give evidence of their main depositional elements. As they are fluvial, we largely follow Miall's concept [(Miall, 1996) and references herein]. So, detailed sedimentological-stratigraphical and architectural reconstructions of the most interesting outcrops have been made, evidencing channel and interchannel architectural units (Costamagna and Barca, 2008). Generally, in SW Sardinia, the Cixerri Fm. is well-exposed especially in the Cixerri and Giba basins central area: here, it is most likely represented by the middle to upper part of the unit. The main depositional feature is a low-sinuosity stream environment. It was formed by ribbon and single-story sandy channels with a W/D ratio of 15 to 20, flowing towards east, gradually loosing energy in the same direction (Trexenta area): also the coarse/fine deposits ratio decreases in that direction. Similarly, the importance of the channel elements progressively diminished in respect to the interchannel floodplain ones. Channel elements are frequently featured by grey to light grey sandy side bar and more rare point bar sequences. They are separated vertically from each other by rather thick, usually reddish overbank pelites containing scattered crevasse splays. The width mean channel calculated on the basis of the measure of the lateral accretion elements is supposed no more than 15 to 20 m. The depth, determined on the base of single channel fill element thicknesses, was no more than 2 to 2.5 m. In the axis of the Cixerri basin, clast imbrications and through cross-bedding suggest a regional slope inclination toward the East.

Interestingly, in the Monastir area the Cixerri Fm. fluvial facies alternated with siliciclastic deposits containing marine ichnofacies and tidal stratal pattern. This may suggest at least temporary coastal/river mouth areas.

Frequently, along the southern border of the Giba and the Cixerri plains, scattered outcrops with coarse, polygenic and often poorly sorted conglomerates show the development of gravel bars. They probably were laid down in restricted alluvial fan environments directly posed over the pedogenized Paleozoic Variscan basement. Rare paleodirectional indicators suggest a mean north–south transport trend, towards the middle of the present plain and perpendicular to the Cixerri Fm. main channel axis. In this way, the hydrological tributary role played by those fans in respect to the east–west main flow direction is evidenced. The fans are clearly linked to the landscape morphology resulting from the east–west Late Oligocene–Early Miocene rift development. Sometimes these conglomerate bodies seem to sit uncomformably on the Variscan basement, and, also, eroding sandy-muddy deposits of the Cixerri Fm. posed underneath, so suggesting a late deposition time in respect to the Cixerri Fm. itself: thus, these coarse deposits may be attributed to a diverse, younger post-molassic, syn-rift stratigraphic unit.

At Tanca Aru (4 km NW of Siliqua) (Barca and Costamagna, 2000; Ferrara et al., 1995; Pittau Demelia, 1979), a good example of the base of the Cixerri Fm. crops out: it is formed firstly by a brecciated, boulder/cobble calcrete horizon 1 m thick. The calcrete superimposed over a siliciclastic poorly organized deposit resting uncomformably on metasiliciclastics of the Paleozoic Variscan basement. Above, a couple of meters of silty, grey to blackish fluvial overbank and oxbow lake deposits [locally carbonatic and fossiliferous, (Esu and Kotsakis, 1983)] embed and seal a shallow, sheet-like ephemeral, weakly migrating channel: this latter at its base contains a lag deposit formed by poorly sorted quartz angular clasts of centimetric size. Besides, in its lower part this silty horizon also contains many irregular purple Fe-rich nodules most likely resulting from pedogenesis (petroplinthite - Melis R.T., oral comm.) under a warm-humid climate. This basal succession can be followed discontinuously and with troubles due to the poor quality of the outcrops along the whole northern border of the Cixerri basin: about 3 km westward, close to Bainai (Domusnovas), it locally contains lacustrine limestone layers with Characeae algae of Middle Eocene (Lutetian) age (Agus and Pecorini, 1977; Pala et al., 1977). This lower succession is sharply followed by medium-size grained brown to reddish sandstones and pebbly sandstones. Up to now, the lower part of this succession has been assigned by the former authors to the ‘‘Lignitifero’’ stratigraphic unit, basing on a supposed weak unconformity between the silty deposits and the upper sandstones: instead, we believe the lower deposits represent the warm-humid, lacustrine-palustrine start of the fluviatile sedimentation of the Cixerri Fm.: this is also suggested for the Lignitifero stratigraphic unit misses completely either of quartzose conglomerates or boulder/cobble calcretes and petroplinthitic horizons.

In the westernmost Iglesiente-Sulcis outcrops of the Cixerri Fm., located at the western end of the Cixerri basin and in the ‘‘Lignitifero’’ eastern edge basin (Fig. 1, right), the depositional setting changes significantly: distal sandy braided river environments have been characterized. They were formed by frequently interconnected, sheet to tabular-shaped, sandy amalgamated multi-story channel bodies (Fig. 2), some of them migrating rapidly sideways. They are alternated with pelitic overbank bodies often strongly calcretized. Here, channel and overbank successions are fairly balanced in thickness. This indicates the slope gradient and the prevailing provenance of the main bulk of the detritus from the west. In particular, at Flumentepido quarry (Carbonia), where one of the most continuous continental succession of SW Sardinia crops out (Fig. 3, 33 m), the distal braided sandy fluvial deposits pass gradually upwards to low-sinuosity meandering deposits featured by fine overbank deposits and migrating sandy channel bodies: at this point of the succession, overbank deposits pretty prevail over the channel ones.

In some of these western outcrops of the Cixerri Fm. (Flumentepido quarry, Acqua sa Canna, Porto Paglia, M. Sirai: Figs. 2–5) the lower energy sedimentation (from distal braided to low-sinuosity meandering environment, sandy to pelitic in grain size) is replaced almost suddenly to coarse, cobbly deposits of immature conglomerates and sandstones shaped as lens or tabular bodies of some meters in size. Besides, intercalations of pyroclastic deposits of Early Miocenic age (Corona Maria Unit) (Assorgia et al., 1992a) as well as pyroclastic pebbles have been found here. In the Flumentepido quarry area (Carbonia), the deposits are gravelly, imbricated, locally cross-bedded bars, intercalated with lens-shaped cross-laminated sandy bars. The latter represent the fill of entrenched minor channels incised during waning floods. The beds exposed configure a high-energy braided environment. At Acqua Sa Canna (Fig. 5A) and Porto Paglia (Gonnesa), the continental succession is essentially built of an alternation of unchannelized, hyperconcentrated or clast-rich debris flows and rarer stream floods gradually passing towards the top to channelized stream floods embedded in sheet floods. Locally, the finer lithologies contain little rounded pumice, suggesting a partially epiclastic nature. They figure out environments located between the proximal and middle-distal fans under intermediate climatic conditions. Imbrications of clasts and channel cross-sections suggest a source posed westward to Sardinia. Nevertheless, scattered data pointing to an eastern provenance of some depositional episodes had to be mentioned.

Also, at the top of M. Sirai, 1 km WNW from Carbonia, immediately below the pyroclastic cover of the Corona Maria ignimbritic Unit (Assorgia et al., 1992b), few meters

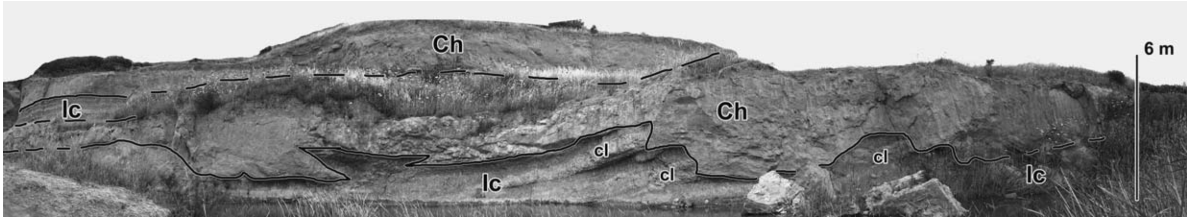

Fig. 2. Flumentepido quarry low front (Carbonia), Cixerri Fm.: amalgamated sandy channels (Ch) cutting pelitic interchannel overbank deposits (Ic) locally interested by strong calicization phenomena (cl).

Fig. 2. Partie inférieure de la carrière de Flumentepido (Carbonia), Fm. du Cixerri : canaux sableux (amalgamés) (Ch) recoupant les dépôts pélitiques d'inter-canal (Ic), avec de nombreuses calcretes (cl) localement.

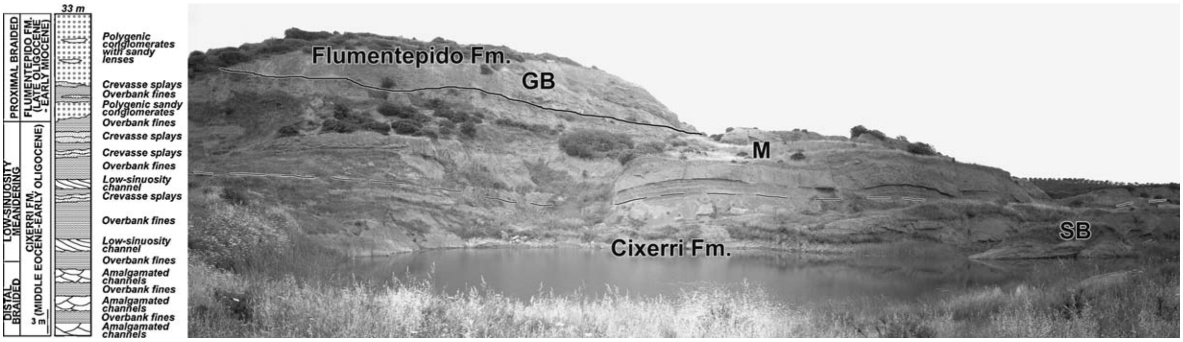

Fig. 3. Lithostratigraphic section of the Flumentepido quarry (Carbonia) (33 m); SB: sandy braided stream; M: low-sinuosity meandering stream; GB: gravelly braided stream.

Fig. 3. Section lithostratigraphique (33 m) de la carrière de Flumentepido (Carbonia) ; SB : (faciès de) fleuve entrecroisé sableux ; M : fleuve à méandres avec faible sinuosité ; GB : (faciès de) fleuve entrecroisé graveleux.

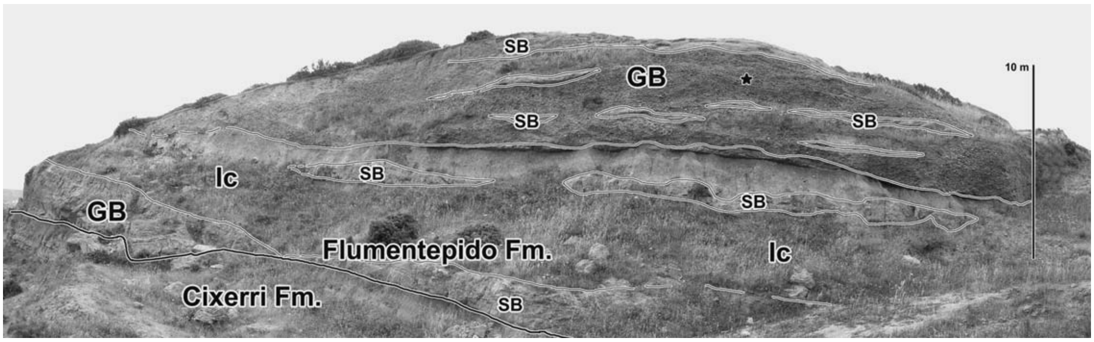

Fig. 4. Flumentepido quarry upper front (Carbonia); Flumentepido Fm.: channelized deposits formed by gravelly bars (Ch) with subordinated sandy lenses filling incised secondary channels (SB), alternated with interchannel pelitic deposits (Ic); this unit rests on the migrating, low sinuosity channel deposits of the Cixerri Fm. F: fault. The black star marks the presence of volcanic clasts.

Fig. 4. Partie supérieure du front de la carrière de Flumentepido (Carbonia), Fm. de Flumentepido : dépôts canalisés de barres graveleuses (Gh) avec des lentilles sableuses subordonnées remplissant des canaux mineurs (SB), en alternance avec les dépôts pélitiques d'inter-canal (Ic). Cette unité repose sur les dépôts canalisés à faible sinuosité de la Fm. du Cixerri. F : Faille. L'étoile noire designe l'endroit de la découverte des galets volcaniques.

of polygenic conglomerates with a significant content of volcanic cobbles are exposed. These conglomerates sit on sandstones and pelites (the direct contact is obscured by the colluvium and vegetation). These outcrops can be easily lithostratigraphically correlated with the Flumentepido quarry succession, located less than 1 km northwestward: here, as described above, proximal braided stream polygenic conglomerates are exposed in the upper part of the front.

The intercalated ignimbrites (Acqua Sa Canna: Fig. 5B) and the volcanic pebbles of the conglomerate layers (Flumentepido, Porto Paglia, Acqua Sa Canna, M. Sirai,: Figs. 2, 3, 4, 5A) can be correlated with to the calc-alkaline volcanic cycle beginning between at 32–28 MA: their

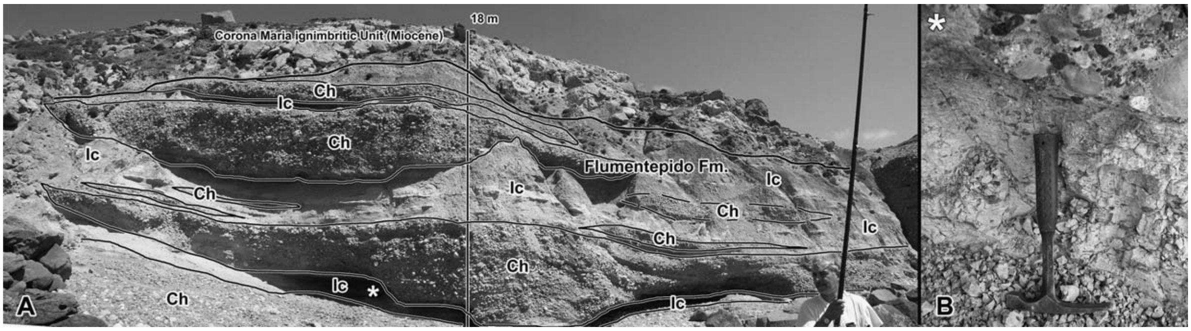

Fig. 5. Acqua Sa Canna Lateral Cliff (Carbonia): A) stream floods of the Flumentepido Fm. superposed by the Early Miocenic ignimbrites of the Corona Maria Unit (Burdigalian); Ch: channelized deposits; Ic: interchannel deposits. The asterisk evidences the ignimbritic interstratified layer; B) Close up of the bentonitized ignimbritic layer: the coarse conglomerates of the Flumentepido Fm. rest above.

Fig. 5. Falaise latérale de Acqua sa Canna (Gonnesa) : A) *Stream flow* dans la Fm. de Flumentepido et ignimbrites de l'Unité de Corona Maria (Burdigalien, Miocène inférieur) sus-jacentes ; Ch : dépôts canalisés ; Ic : dépôts d'inter-canal. L'astérisque indique l'épisode ignimbritique interstratifié : au-dessus se situent les conglomérats de la Fm. de Flumentepido ; B) détail qui montre le feuillet ignimbritique altéré en bentonite, les conglomérats grossiers de la Fm. Flumentepido recouvrent ce dernier.

finding significantly rejuvenates this part of the unit. Besides, to the Corona Maria Ignimbrite Unit (Assorgia et al., 1992a,b), sit on the Acqua sa Canna outcrop a Burdigalian age has been assigned, so referring it to an Early Miocene age.

3. Petrographical and mineralogical data

Arenaceous and conglomeratic cobbles and sandstones collected from the coarse- to medium-size grained outcrops of the Acqua sa Canna and Flumentepido areas have been analyzed.

The Acqua sa Canna conglomerates show a very variable composition: they are constituted of undeformed sedimentary Mesozoic and Cenozoic elements (carbonates and siliciclastics, those latter formed by sandstones and subordinated conglomerates) and minor Variscan Paleozoic schistose elements, with a microconglomeratic-sandy matrix: rare volcanic pebbles are also present. A strong percentage of undeformed conglomeratic cobbles is just formed by not-stressed, decimetric, generally carbonatic rounded elements aged prevalently to Mesozoic and rarely to the Tertiary (macroforaminifera limestone facies of the "Miliolitico" *Auct.*: Early Eocene, Ilerdian). This suggests those conglomeratic cobbles originated from reworked post-Early Eocene terrigenous, most likely continental successions. At those times, high-relief landscapes were at least partially covered by terrigenous continental deposits. The data above so imply the upper part of the Tertiary continental sediments cannibalized the early part.

The modal analysis (Fig. 6) of the coarse sandstone cobbles deriving from the reworking of the undeformed lower part of the post-Early Eocene successions and collected from the Acqua sa Canna and Flumentepido upper conglomerates shows a different composition compared with those collected from the interstratified sandstone layers posed between the thicker conglomerate beds in the same outcrop (Figs. 2, 3, 4, 5A). The Dickinson plot (Dickinson et al., 1983) infers a derivation from a recycled orogen for the sandstone cobbles, while the interstratified sandstones show an origin from a dissected arc. This suggests an important change of the geodynamic scenario between the lower and the upper part of the continental succession of SW Sardinia: this separation is well marked by the pretty sudden passage from low-energy braided environments to the high-energy fluvial braided system of Flumentepido and to the Acqua sa Canna alluvial fan. While the lower part of the succession is still linked to the dismantling of the Pyrenean orogenic wedge (Barca and Costamagna, 2000; Cherchi, 1979), reversely the upper succession results at least in part from the erosion of a volcanic arc: most likely, is this the volcanic arc connected with the Apulia subduction under the European Plate, giving place to the Apennine wedge. Wide remains of the volcanic arc crops out here and there in the Sulcis-Iglesiente plains, and, in general, all over across Sardinia (Assorgia et al., 1992a; Assorgia et al., 1992b; Lecca et al., 1997).

Because of the presence of such a lithological and environmental change (feeding, energy, fluvial style) of regional importance and the chronological implication due to the finding of volcanic elements of Early Miocenic age, it is not recommended anymore to refer the continental succession of SW Sardinia as a single formational unit. It is suggested to keep name the molassoid Pyrenean lower succession as Cixerri Fm., while for the upper part we propose the name Flumentepido Fm.

4. Discussion and conclusion

The data above allow us to define a more precise stratigraphic, paleodepositional and geodynamic evolutional frame of the continental successions of SW Sardinia (Fig. 1 top left).

Almost all outcrops located in the lower part of the continental succession of the Giba and Cixerri basins, of the eastern "Lignitiferous" basin, and of the southern Sardinia basin (Trexenta) area (Figs. 1 right and 7A) can be referred to the Cixerri Fm. The depositional persistence of the unit and the missing of evident, marked erosional surfaces along the succession, allow a more secure attribution of the top age of the Cixerri Fm. *s.s.* to the Early Oligocene. These

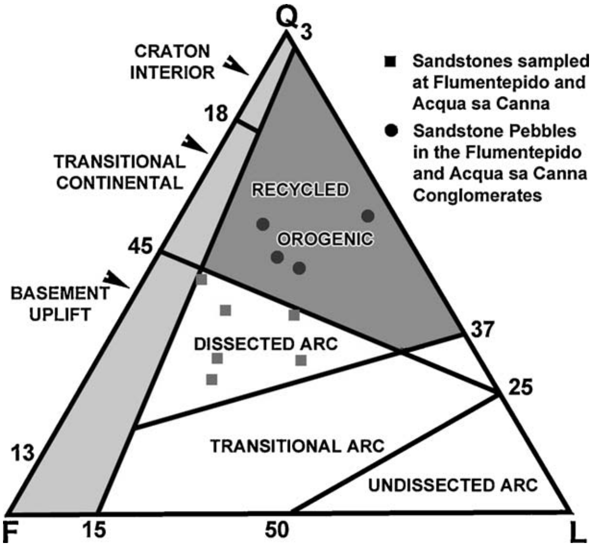

Fig. 6. Modal framework of sandstone pebbles in conglomerates and sandstones sampled at Flumentepido and Acqua sa Canna outcrops. Discrimination fields after Dickinson et al. (1983).

Fig. 6. Composition modale des galets arénacés échantillonnés dans les conglomérats et le grès affleurant à Flumentepido et Acqua sa Canna (diagramme après Dickinson et al., 1983).

outcrops represent the distal dismantling product of the Pyrenean orogenic wedge figuring out an alluvional system formed by ephemeral, braided streams trending in an eastward direction and gradually changing fluvial style to a meandering one. This way, the regional slope decreases towards the east, as well as the energy, with the increasing distance from the Pyrenean orogenic belt located westward (Fig. 7A). The mainly single-story filling of the channels testifies to a network of ephemeral waterways. Thus, the alluvial plain accretion took place only through aggradation: all phenomena were due to rare flood episodes. The spotted calicitized layers mark periods of scarce sedimentation. The climate should have been characterized by intense rainfall episodes from time to time, under a sub-arid climate. This is an important change in respect to the older humid-subhumid tropical climate hypothesized for the Paleocenic–Early Eocenic successions (Murru et al., 2003). This latter, on the contrary is in good agreement with rapid climatic oscillations found (Ferrara et al., 1995) at Tanca Aru in the basal part of the Cixerri Fm.: actually, the petroplinthitic profile defines alternations of humid and dry climates.

It is likely that some main east–west morphological features in southern Sardinia were present even before the rift development (Fig. 7A): the Oligocene–Miocene tectonics only rejuvenated a former mature landscape, perhaps reactivating pre-existing tectonic lines (Fig. 7B). In fact, the Cixerri Fm. principal streams mainly flowed from west to east, perpendicularly to the now north–south tectonic axis of the Sardinian Pyrenean deformations (Barca and Costamagna, 1997a; Barca and Costamagna, 2000). Besides, stream paleodirections from the northwest (Vallermosa, Monastir) suggest in the lower fluvial reaches

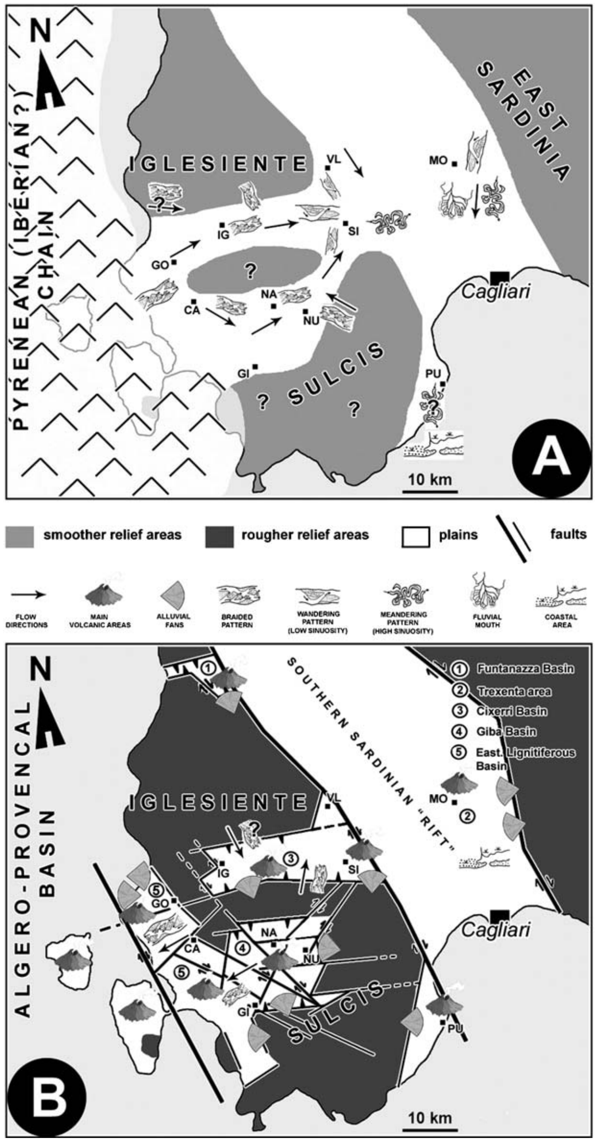

Fig. 7. Sketch map of the paleodepositional and structural frame of the Cixerri Fm. (Middle Eocene–Early Oligocene) (A) and of the Flumentepido and Ussana Fms. (Late Oligocene–Early Miocene) (B) in southern Sardinia, the smoother, passing in time to rougher relieves are built of Paleozoic and Mesozoic rocks; the alluvial plains, probably more hilly close to the relieves, are constituted by Tertiary volcanic and sedimentary deposits. In the evidenced fan areas, the flow directions coincide with the fan spreading directions. CA: Carbonia; GI: Giba; GO: Gonnesa; IG: Iglesias; MO: Monastir; NA: Narcao; NU: Nuxis; PU: Pula; SI: Siliqua; VL: Vallermosa.

Fig. 7. Tableau paléodepositionnel et tectonique schématique de la Fm. de Cixerri (Eocène moyen–Oligocène inférieur) (A) et des Fms. de Flumentepido et de Ussana (Oligocène supérieur–Miocène inferieur) (B) dans le Sud de la Sardaigne, « Les zones les plus planes qui passent progressivement à des reliefs plus accidentés sont constituées de roches paléozoïques et mésozoïques ; les plaines alluviales, probablement plus collineuses vers les reliefs, sont formés de dépôts sédimentaires et volcaniques. Dans les cônes alluviaux, les directions de flux coïncident avec les directions d'expansion des cônes ». CA : Carbonia ; GI : Giba ; GO : Gonnesa ; IG : Iglesias ; MO : Monastir ; NA : Narcao ; NU : Nuxis ; PU : Pula ; SI : Siliqua ; VL : Vallermosa.

secondary (?) slopes NW/SE-oriented, and so more feeding relieves located northwestward.

The termination of the Cixerri fluvial network may sometimes has been located southeastward the Monastir area (Fig. 7A): in fact here, in the Cixerri Fm. fluvial succession, interspaced ichnofacies related to marine environments and tidal hints have been evidenced: so, transitory coastal (estuarine?) environments intercalated with meandering streams may be proposed.

Furtherly, the presence of scattered yellowish marly layers in fine siliciclastic deposits in the Pula area (Fig. 7A) also suggests here a connection with the open sea.

The continental deposits outcropping in the upper part of the Acqua sa Canna, Porto Paglia, Flumentepido (Fig. 2, 3, 4, 5A), and Monte Sirai successions point out a sudden, marked change of the depositional parameters and, consequently, of the fluvial style. These outcrops pertain to higher energy environments, linked to a sharp change of the morphology likely due to a rapid uplift: the sandstone lithologies fall pretty exclusively in the "dissected arc" field (Dickinson et al., 1983). The presence of volcanics, both in place and reworked, belonging to the Oligocene–Miocene cycle [(Lecca et al., 1997) and references therein], allows us to relate these deposits to the starting erosion of the volcanic arc connected with the timing of the Apennine orogeny. The Corona Maria unit, Burdigalian (Early Miocene) in age, rests on those high-energy fan deposits, so fixing a precise upper age constrain to the outcrop. Thus, these deposits can be referred to the Flumentepido Fm. and aged Late Oligocene–Early Miocene.

In addition, also the previously mentioned coarse-grained siliciclastic alluvial fan deposits outcropping along the southern border of the Cixerri and Giba basins (Fig. 7B) and covering unconformably the Cixerri Fm. seem to pertain essentially to the upper part of the depositional cycle of the SW Sardinia continental succession: so they may be referable too to the Late Oligocene–Early Miocene Flumentepido Fm.

It is likely in the Sulcis-Iglesiente that other outcrops refer to the Flumentepido Fm.: as example, we can point the conglomeratic belt poorly outcropping along the state road 126 Gonnesa-Carbonia and posed exactly underneath the volcanic product of Early Miocenic age. Unfortunately, a generalized attempt to differentiate in detail the Flumentepido Fm. from the Cixerri Fm. fails because of the macroscopic lithological affinities, the lack of fossils, and the absence of clear and laterally extended boundary erosional surfaces between the lower and the upper part of the Tertiary continental succession. Further separation attempts are going to be made using as tools petrological and geochemical analyses on the sandstone lithologies, trying also to state precisely the paleogeographic provenance of the detritus contained into the higher energy deposits.

Based on the exposed data, the continental succession of SW Sardinia would expand its existence from the Middle Eocene (Lutetian) at least up to the Early Miocene (Aquitanian), changing in times its tecto-sedimentary meaning. It starts as a molassoid unit accumulating not far from the southeastern border of the Pyrenean (Iberian?) Chain and feeded by its dismantling (Barca and Costamagna, 2000). Along the Eocene, as indicated by the Carbosulcis drills (Assorgia et al., 1992a; Assorgia et al., 1992b), the unit gradually fines up for the progressive smoothing of the Pyrenean (Iberian?) relieves. Nevertheless, the sudden coarsening of the upper part of the deposits under inspection, together with its intimate association with magmatic products of Early Miocenic age (Corona Maria Unit) (Assorgia et al., 1992a,b), and the variable (eastern to western) provenance of the detritus, imply their products are related to the development of the Sardinian Tertiary Rift (Fig. 7B) (Cherchi and Montadert, 1982) in the frame of the coeval Western Mediterranean rifts alongside to the detachment of the Corsica-Sardinia block from the eastern part of the Iberian microplate, so leaving behind the Languedoc-Provençal area and creating the Algero-Provençal basin. So, at that time, the SW Sardinia continental deposits terminate to exist as Pyrenean Molasse – the *s.s.* Cixerri Fm., a pre-rift unit – and gradually starts to play the new role of rift margin succession: the Flumentepido Fm., a syn-rift unit. So, if comparing the depositional environment and tectosedimentary meaning, this Flumentepido Fm. is similar and coeval of the Ussana Fm. (Pecorini and Pomesano Cherchi, 1969), a syn-rift siliciclastic unit outcropping along the eastern border of the southern Sardinian Rift of central-southern Sardinia, but at the same time it differs from it for feeding type and provenance area, and, at some extent, also for the sedimentary environment too, the Flumentepido Fm. one being probably less energetic. In this setting, the tectonic deformations (reverse faults) mentioned in the Flumentepido quarry (Barca and Costamagna, 2000; Carmignani et al., 2004) and up to now framed with troubles into a precise tectonic context could be linked to the Oligocene–Miocene transpressive-transtensive tectonics that give place to the Giba and Cixerri subsiding (pull-apart?) depositional basins (Fig. 7), which shoulders provided at least part of the alimentation of the Flumentepido Fm. in SW Sardinia. In this frame the Funtanazza, Cixerri and Giba basins have a half-graben, structure: in fact, they all are featured by southern east–west master faults, marked by syn-sedimentary thick high-energy early deposits and crossed by magmatic fractures feeding intrusive domes and pyroclastics either. Conversely, the northern east–west faults are never so evident: often the unconformable resting of the Cixerri Fm. over the Variscan basement crops out and the volcanics are scarce and only of pyroclastic origin.

The alluvial fans bordering the southern edge of the Giba and Cixerri basins develop in response to the start of the Late Oligocene–Early Miocene extensional dextral transtensive movements giving birth to the southern Sardinian basin and to the minor Funtanazza, Cixerri and Giba sedimentary basins (Fig. 7B). Most of these coarse-grained sediments of these outcrops mirror the development of a rejuvenating relief and stream tributaries carrying bedload that join quite perpendicularly the main stream of the east–west oriented paleo-Cixerri river catchment basin.

At these times, it is possible that (Fig. 7B): A) the Giba basin, for the developing of uplifting relieves in the Campanasissa area (Narcao-Nuxis-Siliqua sector), separates from the Cixerri basin and so starts to have a watershed of its own, in this way reverting the stream flow direction from about east to south-west; B) the uplift of the Paleozoic highs in the Iglesias–Gonnesa area bars the communications between the Cixerri basin and the eastern Lignitifero basin, so determining a sharp variation of the stream flow from east to west.

So, the different feeding directions found at the Acqua sa Canna succession (Fig. 5A) could be connected with different stages of development of uplifting and sinking Paleozoic highs, posed eastwards and westward of the deposition area, during the opening of the Sardinian Rift.

Finally, the molassic Cixerri Fm. is comparable with some Oligocene Pyrenean molassic deposits [Solsona and younger Ebro basin sequences, (Puigdefàbregas et al., 1986)] and, to a certain extent, perhaps to restricted Bartonian (Late Oligocene) molassic outcrops in the northernmost Provence (Cotillon et al., 1973). While the Flumentepido and Ussana Fms. are probably analogous with some Balearic [Cala Blanca Detrital Fm., Latest Rupelian – Chattian, (Ramos-Guerrero et al., 1989)] and Provençal [“Conglomeratic Rouet” Unit 1, “Parareefal Cap de Nautes” Unit 2 and “Brackish Rousset” Unit 3, Chattian (Conesa et al., 2009)] units related to the first opening of the Algero-Provençal basin.

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