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Stratigraphic-paleogeographic evolution of Eastern Sardinia Jurassic passive margin carbonates: synthesis and future developments

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ABSTRACT - It is presented a synthetic reconstruction of the Eastern Sardinia Middle-Upper Jurassic stratigraphic setting, focusing the most important tectono-sedimentary events and the regional paleogeographic reconstruction, evolution of the carbonate depositional systems. This synthesis is based on data collected during 20 years of studies carried out in collaboration with several students and colleagues of the Carbonate Sedimentology and Stratigraphy research team of Milan University. The most original results refer to the lithostratigraphic revision and depositional architecture of the Kimmeridgian-Tithonian carbonate succession: Tului, Lower Bardia shallow water ramp and shelf margin depositional systems, coeval to the Baunei-S'adde Limestone Pedra Longa open to restricted intraplatform basins and peculiar inner platform carbonates and breccias of the Urzulei Fm. Thick, lenticular intercalations of tithonian poligenic carbonate breccias at the base of the Mt. Bardia Fm. are interpreted as mass transport events associated to large collapses of the platform margin. The breccia bodies are probably related to a tithonian tectonic activity with the reactivation of jurassic growth faults and a local flexuring. To improve our understanding of the detailed biological-sedimentological response of the Middle-Upper Jurassic shallow-water carbonates charactering the evolution of the Sardinia passive margin, new high-resolution ages are required and correlations with the coeval Tacchi and Nurra successions.

Keywords: stratigraphy; paleogeography; Middle Upper Jurassic eastern Sardinia; shallow water carbonates.

1. INTRODUCTION

During the Mesozoic, Sardinia belonged to the European Peritethys domain. Its Jurassic stratigraphic evolution is comparable, for sedimentary and climatic-paleogeographic characteristics, to coeval successions in NE Spain and SW Provence, that record the Middle Jurassic rifting phase affecting the south European margin of the Tethys (Dercourt et al., 1994, 2000 and references therein). The 500-700 m thick Middle-Upper Jurassic carbonate succession of Eastern Sardinia documents the presence of an articulated NE-SW trending Jurassic structural high close to a deep, erosional type escarpment, documented by the coeval Longobucco basinal succession (Calabria) (Santantonio et al., 2016; Costamagna, 2016). The Upper Jurassic stratigraphy and facies evolution of eastern Sardinia high (Fig. 1), however, are poorly indicative for a very close location of this escarpment. The Sardinia high, about 75 km wide, was dominated by deposition of prevalent shallow water deposits, with low accommodation rates, up to the Oxfordian. The recent biostratigraphic redefinition of a few Upper Jurassic regional sedimentary events, the well-preserved depositional geometries and the carbonate facies associations permitted: i) to define the geological history of the Eastern Sardinia Jurassic carbonate succession and ii) to reconstruct a more detailed tectono-sedimentary evolution of the well-preserved, but still poorly studied Tethyan passive margin of Sardinia. This succession records regional tectono-sedimentary, climatic and diagenetic events, that control lithostratigraphic boundaries and provides constraints for stratigraphic correlations. Reviews of the local Jurassic lithostratigraphy have been recently proposed by several authors (Dieni et al., 2013; Costamagna and Barca, 2004; Costamagna et al., 2007; Costamagna, 2015, 2016; Jadoul et al., 2009, 2010; Lanfranchi et al., 2008, 2011; Casellato et al., 2012). A last synthesis, modified from Jadoul et al. (2009, 2010), is proposed in figure 1.

The syn-rift Jurassic succession of Eastern Sardinia, mainly preserved in structural troughs, begins with discontinuous lenses (up to 40 m thick) of polygenic fluvial conglomerates, sandstones, lacustrine facies and tidal to coastal marine mixed calcarenites and quartzarenites at the top (Fig. 1, Genna Selole Fm. Costamagna, 2015, 2016 and references therein). The upper lithostratigraphic boundary of this Bajocian-Early Bathonian succession is still matter of discussion, in fact Costamagna (2008, 2015,

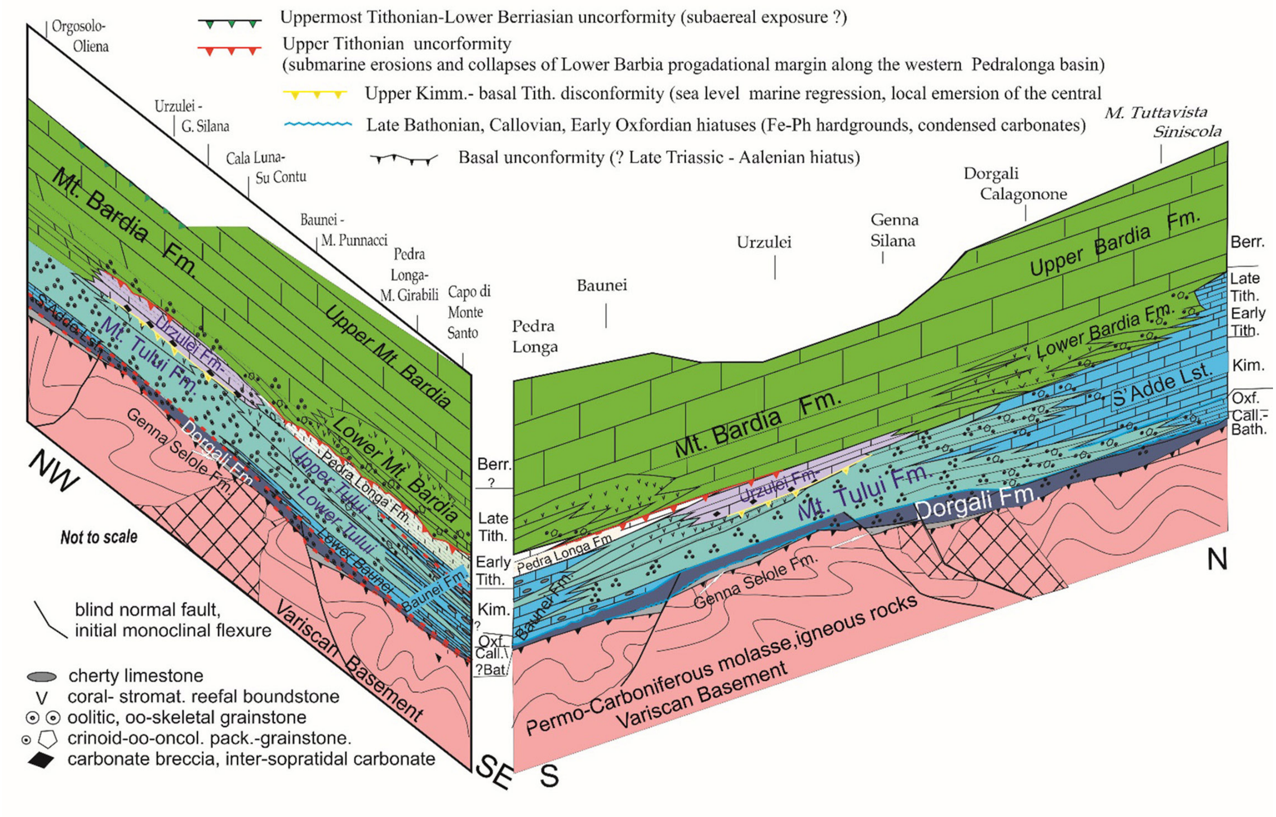


Fig. 1 - Lithostratigraphic schemes of the Eastern Sardinia Jurassic. Modified from Jadoul et al. (2009, 2010).

2016) considers the mixed carbonates with intercalations of siliciclastic as upper Genna Selole Fm. (Usassai-Perdadefogu lithofacies) while Dieni and Massari (1985), Jadoul et al. (2009, 2010) and the previous authors the marine transgression at the base of Dorgali Fm. This siliciclastic unit is overlain by 450-650 m of Bathonian to Early Berriasian prevalent shallow-water carbonates: Dorgali, Mt. Tului and Mt. Bardia formations (Amadesi et al., 1960). This lithostratigraphic subdivision is still reliable: these historical formations document quite well the main stratigraphic, evolution of a regional, persistent shallow-water carbonate depositional system characterized by different architectures, lithofacies associations and accomodation rates.

2. STRATIGRAPHIC AND PALEOGEOGRAPHIC EVOLUTION

1) The first dated marine deposits, covering a pedogenized Variscan Basement or the Middle Jurassic continental succession, are Early Bathonian in age (Dieni and Massari, 1985; Dieni et al., 2013; Costamagna, 2015 and references therein) and is quite coeval with the main marine transgression on structural highs of south France (Charcosset et al., 1996). The first marine cycle (mainly Bathonian), (Perda Liana Mb, Dieni et al., 2013; and Dorgali Fm., 1, 2 in figure 2) documents a coastal paleogeography with open bays generally characterized by low accommodation. Transgressive, open marine, fine-grained bioturbated to bioclastic limestones with siliciclastic inputs at the base evolve to oolitic, mainly dolomitized, grainstone towards the top. This sequence, more than 100 m thick southward (Tacchi area, Dieni et al., 2013), is thinner in the north-eastern areas, (10-40 m in the Baunei-Dorgali Supramonte, Mt. Albo successions, Costamagna, 2016). The first regional depositional hiatus, recorded by Fe- rich hardgrounds (Upper Bathonian after Dieni et al., 1966) frequently associated with siliciclastic input, marks the top of this unit (3 in figure 2). Coeval Fe-rich hard grounds\firmgrounds are also present southward in the Tacchi outcrops of the Upper Genna Selole Fm. (Costamagna, 2015, 2016).

2) The overlying Lower Callovian-Lower Oxfordian shallow water carbonates (3 in figure 4) upper Dorgali Fm. or the coeval open marine carbonates at the base of the Sadde and Baunei fms. (2 in figure 4), are thinner and locally dolomitized. They are characterized by a few regional hardgrounds\firmgrounds developed during a transgressive trend, with long periods of non-deposition, controlled by global decrease of carbonate production. In particular, the Middle-Late Callovian hiatus is represented by thin Fe-Phosphate-Qz rich crust or by a very thin fossiliferous calcareous horizon (3 in Fig. 4) (Dieni et al., 1966). The Early Oxfordian is also frequently condensed in the fine grained, bedded limestones of the northern Siniscola-Posada Basin characterized by oncolitic pelagic facies (Massari and Dieni, 1983) near the base of the S'Adde Fm. (Casellato et al., 2012). This facies association, coeval with the condensed successions of other Middle Jurassic structural highs of the northern

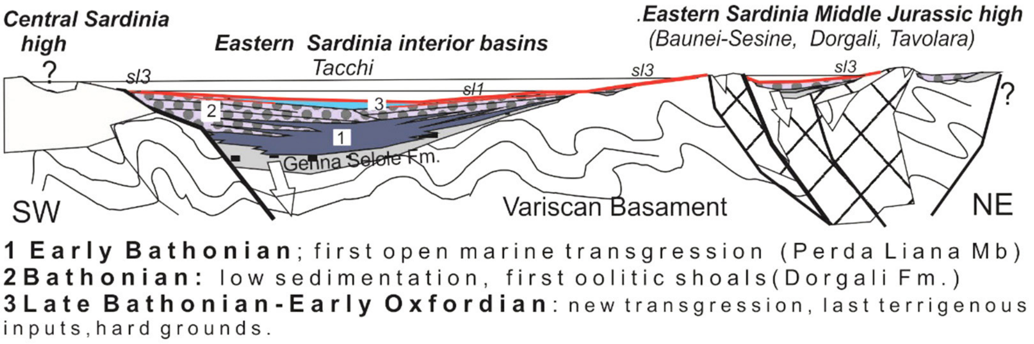


Fig. 2 - Stratigraphic profile with the evolution of the first Middle Jurassic sedimentary cycle (Genna Selole-Perda Liana-Dorgali fms, 1, 2) and the Callovian-Early Oxfordian low sedimentation (3).

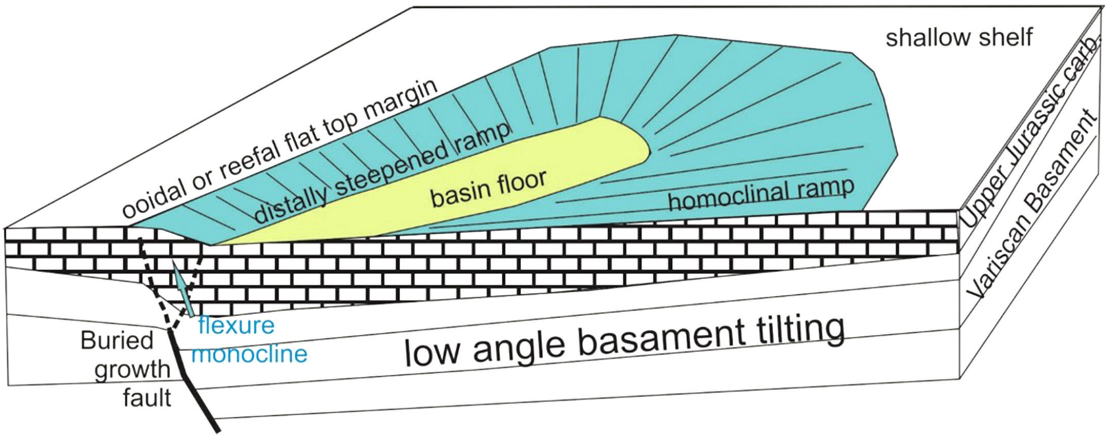


Fig 3 - Model of intraplatform half graben basin, generated by the reactivation of growth faults and the development of a flexure.

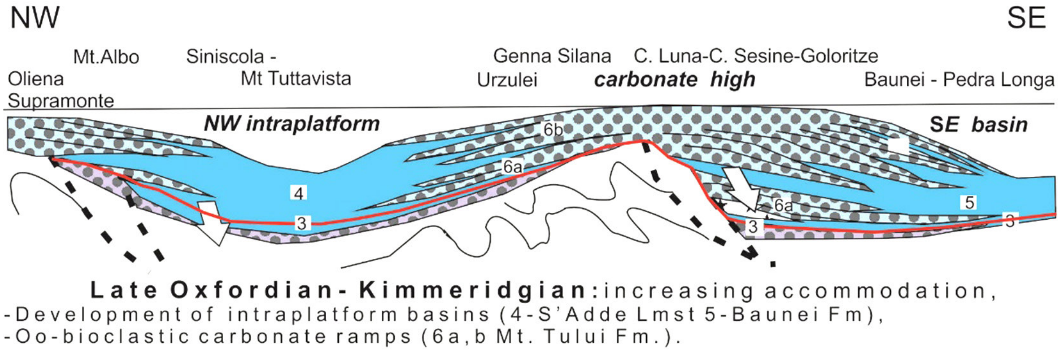


Fig. 4 - Oxfordian-Kimmeridgian stratigraphic profile with the depositional geometries, stratigraphy of shallow water oo-bio calcarenites of Tului ramp depositional systems (6a, 6b Lower and Upper Tului Fm.) and bedded calcilutes\calcisiltites of the Northern intraplatform Basin (S'Adde Lmst. 4) and southern basin (Baunei Fm., 5).

margin of the Tethys (Dercourt et al., 1994 and references therein), is related to global climatic and oceanographic revolution related to important geodynamic changes in the Western Tethys (Dercourt et al., 2000). The condensed Oxfordian basinal carbonates also suggest a regional carbonate production crisis, in particular during the Late Callovian-Early Oxfordian, recently associated with a cooling climatic event (Tremolada et al., 2006; Louis-Schmid et al., 2007).

The youngest episode of condensed sedimentation in the northern basin is, locally (Siniscola), associated with sedimentary dikes (Casellato et al., 2012), rare slumpings and increase in the accommodation space, possibly related to syn-sedimentary tectonics which led to the development of half-graben basins (Figs. 3, 4). The absence of talus breccias and evident erosional escarpments suggest the development of blind normal faults in the Variscan Basement (Figs. 2, 3). In the Urzulei Supramonte, at the base of the carbonate high carbonate succession (Fig. 1), is present a lenticular intercalation, up to ten meters thick, of coarse, chaotic carbonate breccias with clasts of intraformational shallow water limestones (Lower Tului Fm.), lithified, fractured dolostones of the underlying Dorgali Fm. embedded in a locally aboundant matric consisting of oolitic grainstone. Geometries and the facies organization of this polygenic breccia (Oxfordian in age?) are quite similar to the overlying and nearly outcropping tithonian breccia (upper Urzulei Fm., 9c in figure 6). Both these breccia bodies are interpreted as collapse breccias, possibly associated to a flexuring of the shallow water jurassic carbonate cover due to the reactivation (mainly in the Variscan Basement) of a listric growth fault with growth strata in the jurassic carbonate (Fig. 3). The presence of blind growth faults may also have controlled the accommodation and paleogeographic evolution of all the overlying Upper Jurassic shallow-water carbonates.

In the Southern Basin a T\R cycle (up to ten meter thick) with at the top the first, meter size, coral patch reefs could represent the top of the Oxfordian (Fig. 1, base of the Tului Fm.). A Late Oxfordian regressive trend, documented by basinward progradation of shallow-water carbonates (Fig. 4) is also observed in the northern basinal succession of M. Albo (reference section of S'Adde Lmst. of Dieni and Massari, 1985; Casellato et al., 2012).

3) An Early Kimmeridgian transgression and a regression at the base of the Tithonian (after Jadoul et al., 2010; Late Kimmeridgian according to Dieni and Massari, 1985; Costamagna and Barca, 2004; Costamagna et al., 2007) has been recognized (Upper Tului, Upper Baunei and S'Adde fms.; Fig. 1) have been recognized both in the northern, southern basins (Upper Tului, Upper Baunei and S'Adde fms.; 4, 5, 6b in figure 4). The Early Kimmeridgian transgressive trend and the development of carbonate ramps (Mt. Tului Fm.) may be also a consequence of inferred Early Oxfordian tectono-sedimentary, oceanographic events. This transgressive trend is recorded by progradation of inner-middle ramp oo-bioclastic grainstone (Lower Tului, 6a in figure 4) covering well bedded, fine-grained distal ramp carbonates (S'Adde and Lower Baunei fms.). The shallow-water carbonates firstly nucleated on a central carbonate high (at present- W-E orientated) (Urzulei/Oliena, Codula Sesine/Codula Luna, South Mt. Albo), facing a North-Western (Cala Gonone, M. Tuttavista, North Mt- Albo-Siniscola-Posada) and a South-Eastern intraplatform basins (Baunei, Pedra Longa, Jerzu) (Figs. 1, 4).

The shallow-water kimmeridgian facies associations of Mt. Tului Fm. are dominated by ooids, coated/aggregate grains, oncoidal grainstone in the inner ramp, whereas fine-grained grainstone/packstone rich in

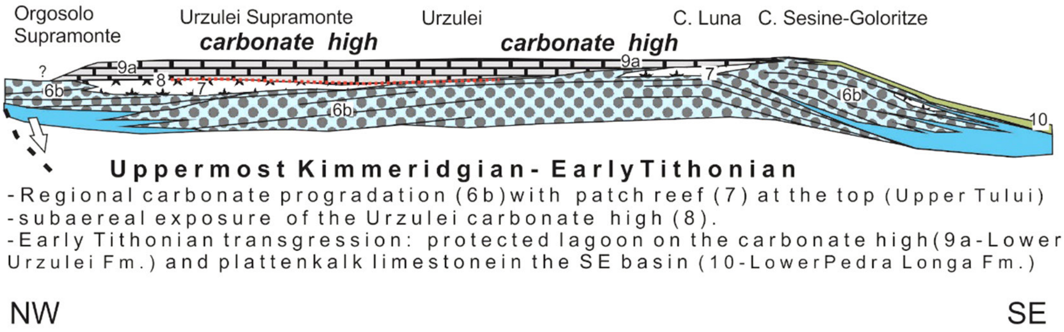


Fig. 5 - Late Kimmeridgian-Early Tithonian stratigraphic evolution of the upper Tului (6b), locally with reefal carbonates (mainly westward, 7), the regional regression (carbonate breccias with black pebbles, 8) associated with brackish lagoonal carbonates of Lower Urzulei (9a) (Lanfranchi et al., 2008) on the carbonate high and more open marine calcilutites eastwards (Lower Pedra Longa "plattenkalk" facies) (10).

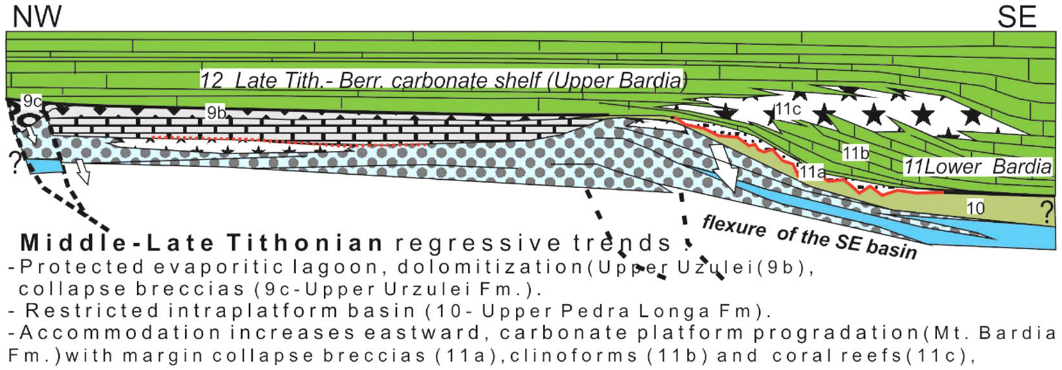


Fig. 6 - Stratigraphic profile during the Upper Urzulei regressive facies (westward, 9b), the upper Pedra Longa (10) and the eastwards progradational depositional systems of lower Bardia (11 a,b,c).

crinoid fragments are more frequent in the middle ramp. Coral-calcareous sponge patch reefs are well-developed at the top of the Kimmeridgian T/R cycle (top of Tului Fm, latest Kimmeridgian-Early Tithonian, 7 in Fig. 5). The reefal carbonates (1st coral limestone regional marker) are characterized, at the base, by fine to coarse grained bioclastic grainstone with stromatoporoids, ooids and, at the top, by coral, stromatoporoid and chaetetid boundstone (Jadoul et al., 2010). These bioconstructions typically crop out along the western peripheral areas of the "central carbonate high" (Urzulei Supramonte, and Su Conte-Cala Sesine Supramonte) and document the high stand last progradation of the Tului Fm. shallow carbonates (6b in Fig. 5). On the eastern margin of the "central carbonate high (Cala Sesine-Goloritzé) the Upper Tului carbonates are represented by amalgamated, thick oo-bioclastic grainstone.

On the western area of the central carbonate high (Urzulei Supramonte, Cala di Luna-northern Baunei Supramonte, Tacchi of Ogliastra) the upper Tului reefal facies are overlain by continental carbonate breccias with black pebbles and peritidal calci-mudstone, wackestone with tepees, fenestrae and charophytes (uppermost Kimmeridgian disconformity of Dieni and Massari, 1985, base of the Urzulei Fm. after Lanfranchi et al., 2008; Jadoul et al., 2010) (8 in Fig. 5).

The basinal/outer ramp facies consist of calci-mudstone and thin peloidal packstone (S'Adde Limestone in the Northern Basin, Baunei Fm. and Pedra Longa Fm. in the Southern Basin). The Upper Kimmeridgian basinal carbonates, rich in cherty nodules, represent a major stratigraphic marker of the Eastern Sardinia Jurassic (Casellato et al., 2012).

Higher frequency cycles (recorded at the base by submarine Fe-hardgrounds\firmgrounds and ramp progradation at the top) have been recognized in the uppermost Kimmeridgian succession of the Southern Basin (Fig. 1, Upper Tului Fm., 6b in Fig. 4).

4) The Tithonian stratigraphy and the paleogeography of carbonate depositional systems is more articulated than considered by all previous Authors (eg. the Mt. Bardia Fm. of Dieni and Massari , 1985; Carmignani, 2000; Costamagna et al., 2004, 2007). The Tithonian of Eastern Sardinia records an increase both of accommodation space and skeletal carbonate production, as documented by up to 550 m thick Mt Bardia Fm. deposited in about 5-6 Ma (Upper Tithonian-Early Berriasian). The Tithonian of Eastern Sardinia is characterized by, at least, three regional tectono-sedimentary, climatic events (from Early up to Late Tithonian): a) the Pedra Longa open to restricted\ intraplatform basin, b) the Urzulei inner platform, brackish environments, c) the carbonate breccias present in different stratigraphic positions.

The thick Tithonian-Berriasian T|R mega cycle (Pedra Longa or Urzulei fms. and overlying Mt. Bardia Fm., Fig. 1) characterizes the middle-upper stratigraphic position of all the carbonate successions from Tortoli to Golfo degli Aranci. Locally, at the base, a higher frequency Tithonian T\R trend, (Lanfranchi et al., 2008, 3rd cycle) has been recognized both in the coeval Urzulei and Pedra Longa fms. but only in the southern area (9 a,b in Figs. 5, 6).

The stratigraphic evolution of the Bardia depositional system can be divided in two informal units: lower and upper Mt. Bardia Fm.

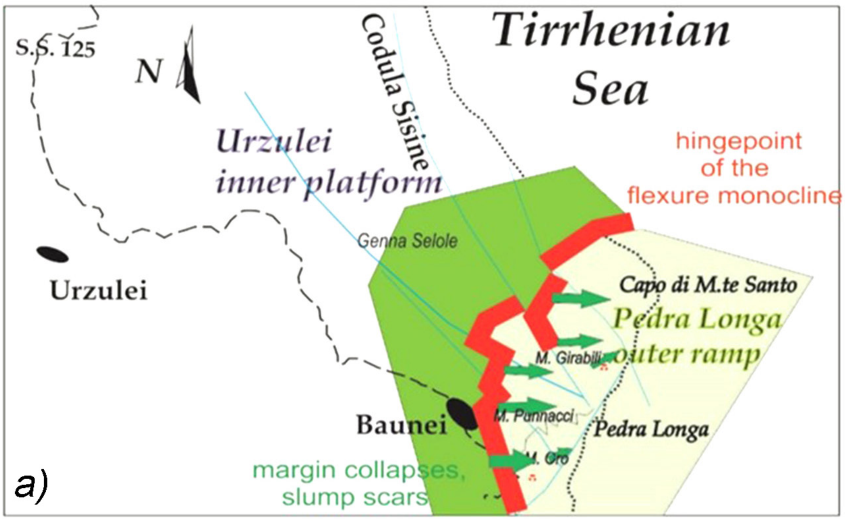
In the SE basin the lower Mt. Bardia Fm. is characterized by a basinward progradation (regional trend towards East)-of sigmoidal clinoforms (M. Punnacci, Cala Sesine) (11b in Fig. 6) with coral-calcareous sponge floatstone and rudstone at the slope break (11c in Fig. 6) (Lanfranchi et al., 2011). The maximum thickness of the lower Mt. Bardia Fm. is up to 180 m eastward, observed where it developed on thick outer ramp fine-grained packstone to mudstone of Baunei-Pedra Longa and S'Adde Limestone successions of the southern and northern basins, respectively (11 a,b,c in Fig. 6). The "plattenkalk" (Swinburne and Hemleben, 1994) calci-mudstones of Pedra Longa Fm. (10 in Fig. 6) are very similar to the coeval basinal "platy limestones" (Courjault et al., 2011 and ref. therein) but also to the Solnhofen Lithographic Limestone of Germany deposited in small, stagnant marine basins surrounded by reefs. In the northern basin the Pedra Longa Fm. is missing, the Mt. Bardia progradation generally begins earlier, during the Early Tithonian (Cala Gonone and Mt. Albo areas; Fig. 1; Casellato et al., 2012) but locally near the end of Tithonian (Mt. Tuttavista). The lower Mt. Bardia Fm. of Cala Gonone and M. Tuttavista is characterized by the presence of well-developed reefal limestones ("2nd regional coral limestone", Late Tithonian, 11c in Fig. 6). Reefs are dominated by a very differentiated association of corals and microbialic coatings and laminations, associated to stromatoporoids, chaetetids, sponges, and an abundant micro-framework, matrix characterized by prevalent skeletal grains coming from the back reef (echinoids, diceratids, nerineids, benthic foraminifera, dasycladacean algae). A detailed, quantitative study of the reefal biofacies of Calagonone is in preparation by Ricci et al. The reefal carbonates of Cala Gonone, Orosei quarries and the subtidal, cyclic carbonates of an undifferentiated Bardia Fm. cropping out along the Orosei Gulf (NE margin of the central carbonate high, Cala Luna-Cala Sesine area) exhibit a typical network of syn- and early diagenetic tensional fractures filled with different generations of shallow marine laminated, muddy, fine graded internal sediments and ooidal grainstone (Lanfranchi, 2009). The origin of these large scale pervasive fracturing, typical of the eastern Bardia massifs, is congruent with the mechanism of formation of the, probably coeval, carbonate breccias bodies present in southern Baunei basin. The lower Mt. Bardia Fm. on the central carbonate high succession is represented by restricted platform mudstone to packstone with common dasycladacean green algae, which were interbedded with diceratids and nerineids floatstone to rudstone and subtidal skeletal packstone/ grainstone, locally oolitic, comparable to the overlying upper Mt. Bardia Fm.

In the southern Baunei basin, the base of the lower Mt. Bardia Fm. is characterized by up to a few decameters thick, chaotic, polygenic carbonate megabreccia (11a in figure 6) recording a regressive trend marked by a sharp, erosional boundary between the thin-bedded Pedra Longa Fm. ("plattenkalk" facies) and the massive Mt. Bardia Fm. This erosional unconformity, observed in a wide area (western margin of the Pedra Longa southern basin, Fig. 7), is characterized in the proximal area by deep erosional incisions in the underlying sediments associated with slump scars, and in the distal area by erosional canyons and debris flow breccias (Fig. 7). Clasts of these breccias derive from prevalent shallow-water inner ramp, lagoonal oo-bioclastic grainstone/packstone and calci-mudstone (Pedra Longa Fm. Plattenkalk facies) and poorly lithified marly limestone (marker horizon at the top of Pedra Longa Fm) that frequently represent also the breccia matrix.

Possible mechanisms for the megabreccia emplacement include: i) catastrophic mass transport due to liquefaction processes in the upper Pedra Longa ("plattenkalk facies"), ii) failures of shallow-water carbonate sands along a restricted intraplatform gentle slope during the first phases of the Mt. Bardia carbonate progradation with several debris flows generated by margin collapses (Figs. 7, 11a in figure 6).

Margin collapses were controlled by Late Tithonian syn-sedimentary tectonics (possibly related to a fault block tilting in the underlying Variscan Basement toward the east) that created a NE-SW flexure-monocline in the upper Jurassic succession of the present day coastal massif of the Orosei Gulf (Fig. 7) and created the accomodation for the Bardia depositional system and, locally the development of thick lower Bardia carbonate facies (11 b,c in figure 6).

The upper Mt. Bardia unit, that frequently corresponds to the undifferentiated Mt. Bardia Fm., consists of up to 350-400 m thick, shallow-water carbonates, dominated by subtidal skeletal-oncoidal grainstone and packstone, stacked in shallowing-upward cycles. Locally thin (up to 1 m) intertidal cycle of stromatolitic bindstone, fenestral ooidal-intraclastic pisoidal packstone/grainstone locally with tepees (Orosei quarries) are present. Regressive metre-scale peritidal cycles cap the Mt. Bardia succession (Dieni and Massari, 1985; Dieni and Radoicic, 1999). The age of the top Mt. Bardia Fm.is Early Berriasian in



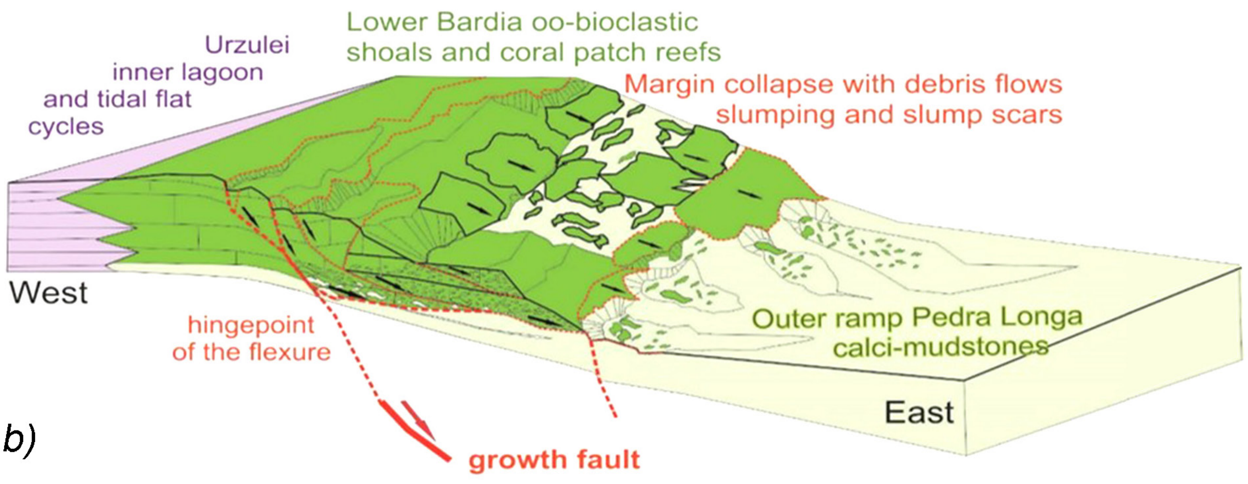


Fig. 7 - a) Depositional model proposed for the chaotic carbonate breccias (Lower Bardia, 11a of figure 6); b) depositional profile along a gentle slope facing the upper Pedralonga calcilutites marly limestones of the southern Baunei basin.

the eastern Orosei Gulf succession, (Dieni and Massari, 1985), in the massif of Oliena (Dieni and Radoicic, 1999) dasyclad algae suggests a still Tithonian age for the uppermost Bardia peritidal carbonates. These data confirm a westwards early nucleation (Early Tithonian) of reduced in thickness, poorly differentiated mainly shallow subtidal Mt. Bardia Fm. carbonates. A progressive younger Late Tithonian progradation (11 in figure 6) occurred eastward in the more or less open and deep intraplatform basins around the carbonate high (Cala Sesine, Jadoul et al., 2010). More northward and westward (Golfo Aranci-Tavolara, M. Albo, Oliena Supramonte), the marker horizons represented by the Urzulei or Pedra Longa facies associations are missing and the Tului-Bardia depositional systems may be amalgamated.

3. CONCLUSIONS

A few nomenclatural problems have yet to be addressed and resolved about the Jurassic lithostratigraphy. A priority is to address a redefinition of the Dorgali Fm., propose as formal lithostratigraphic units the basinal southern succession (Baunei Fm. or as member of the S'adde Limestone) (this unit not corresponds to the "Baunei Group" of Costamagna et al., 2007), Urzulei and Pedra Longa peculiar Tithonian carbonate facies.

- The Tithonian-Berriasian carbonate succession of Eastern Sardinia, described and represented in geological maps as a monotonous carbonate platform succession (eg. the Mt. Bardia Fm. of Carmignani, 2001) is characterized at the base by at least three important tectono-sedimentary events (from the Early up to Late Tithonian). a) The development of Pedra Longa open to restricted\ intraplatform basin (Fig. 3, similar to the depositional environment of Solnhofen plattenkalk. b) The Urzulei peculiar inner platform facies with algae characeae and black pebbles. c) Two different poligenic carbonate breccias: 1) associated to large mass transport processes related to large collapse along gentle slopes during tectonic activity (growth faults and syndepositional flexuring) and or strong storm activity (Seguret et al., 2001); 2) lenticular, coarse and chaotic, matrix rich poligenic breccia, probably coeval with previous ones, interpreted as local collapse events in carbonate-evaporitic facies of top Urzulei (Lanfranchi et al., 2008) or emergence of a growth fault (9c in figure 6). The correct interpretation of these stratigraphic events is fundamental to reconstruct the last jurassic geodynamic setting of Eastern Sardinia and correlations with the coeval facies of Western Sardinia (Nurra, Cherchi and Schroder, 1986) and the Upper Jurassic of South France (eg the "Tithonian breccias" events in the Subalpine basins, Courjault et al., 2011).

- A personal interpretation of the tithonian events is favorable to a genetic model characterized by a gentle block faulting and a regional collapse of the Eastern Sardinia structural carbonate high with an increase of accomodation rates eastward that favored high carbonate productions and optimal conditions for the development of carbonate shallow water depositional systems through all the North Sardinia.

- Further, more detailed studies investigating the chronostratigraphic and the architecture of the shallow water carbonates. In particular, I suggest a more detailed stratigraphic analysis of the Urzulei-lower Mt. Bardia Fm succession in the Tacchi area where a carbonate high succession (similar to the Urzulei Supramonte succession) is locally present. However, to improve our understanding of the detailed biological-sedimentological response of the Upper Jurassic shallow-water carbonates to different controlling factors, new high-resolution ages are required.

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