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STRATIGRAPHY OF THE MIOCENE SYN-RIFT VOLCANO-SEDIMENTARY SUCCESSION IN A SECTOR OF THE CENTRAL-SOUTHERN SARDINIA TROUGH (ITALY)

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Abstract: The Miocene sedimentation in the "Sardinia Trough" has been controlled by tectonic activity, also responsible for strong, basic-intermediate and silicic calc-alkaline volcanism. The volcano-sedimentary succession cropping out near the Villanovaforru village ("Marmilla Basin", central-southern "Sardinia Trough") is the object of this study. The succession has been subdivided into nine new stratigraphic intervals and it is characterized by abundant volcaniclastic materials. In the lower part of the succession some basaltic pillow lavas are interbedded. The nine stratigraphic intervals extend from Early Burdigalian (Zone N5 and N6) to Late Burdigalian (Zone N7) and the microfossil assemblages indicate hemipelagic sedimentation. A deepening of the basin seems to occur in correspondence to the beginning of the volcanic activity. The reconstructed stratigraphic succession of the Villanovaforru area, which is considered representative of the Early Miocene sedimentation within the southern sector of the "Marmilla Basin", shows that a transition from a continental to a marine environment occurred during the "Sardinia Trough" rifting and the drift of the Sardinia-Corsica Block. The extensional tectonics is also confirmed by the high-Mg composition of the basaltic lava flows interbedded in the succession.

Key words: Burdigalian, Sardinia-Corsica Block, lithostratigraphy, biostratigraphy, extensional tectonics, syn-tectonic deposition, volcano-sedimentary succession, "Sardinia Trough".

Introduction, geological setting and objectives

The study of Sardinian geology is an important tool to reconstruct the stratigraphic, tectonic and magmatic events, which occurred during the Neogene geodynamic evolution of the Western Mediterranean area. Between the Late Oligocene and the Early Miocene, rifting of the European Margin caused the opening of the oceanic Algero-Provençal Basin (cf. Gattacceca 2001 and references therein) and the connected Apennine deformation. Normal faulting also affected the area corresponding to the present day Western Sardinia (Cherchi & Montadert 1984; Assorgia et al. 1997a) and originated a NS-striking depression, up to 200 km in length, named the "Sardinia Trough" (Vardabasso 1963; Fig. 1). The coexistence between the extension occurring in the "Sardinia Trough" and the compression originated by the drift and counterclockwise rotation of the Sardinia-Corsica Block towards the east, suggests a strong genetic link between the extensional deformation (internal areas) and the compressional one (external areas), which may be related to a N-NW subduction (Carmignani et al. 1995). The extensional tectonics caused the development of many sub-parallel basins and ridges, bounded by normal faults and cut by transversal minor tectonic features (Oggiano et al. 1995). These tectonic basins are usually asymmetric in shape and they are related to master faults (in the eastern margin) and antithetic faults (in the western margin). However, during the extensional deformation, some compressional events have been recorded by some unconformities and *hiatus* within the sedimentary successions; compressional mesostructures such as joints, faults, pebbles with stylolitic striae and gentle folds have also originated. In its southern sector the "Sardinia Trough" has been overprinted by a minor extensional Pliocene-Pleistocene NW-SE trending structure (the "Campidano Graben", Fig. 1).

The Early Miocene rifting originating the "Sardinia Trough" involved the whole of Central-Western Sardinia, causing a deep paleogeographical change. Several authors proposed interesting geodynamic and paleogeographical models (Coulon 1977; Cherchi & Montadert 1982; Guerrera et al. 1993; Maillard & Mauffret 1993; Carmignani et al. 1995; Vigliotti & Langenheim 1995; Assorgia et al. 1997b; Gattacceca 2001), but little attention has been given to the collection of detailed stratigraphic data, which are of high importance to calibrate the different events. The sedimentation within the "Sardinia Trough" ranges from a fluvio-lacustrine to a marine environment, with abundant volcaniclastic intervals and it shows a marked facies variability which does not allow easy lithostratigraphic correlations. Therefore the de-

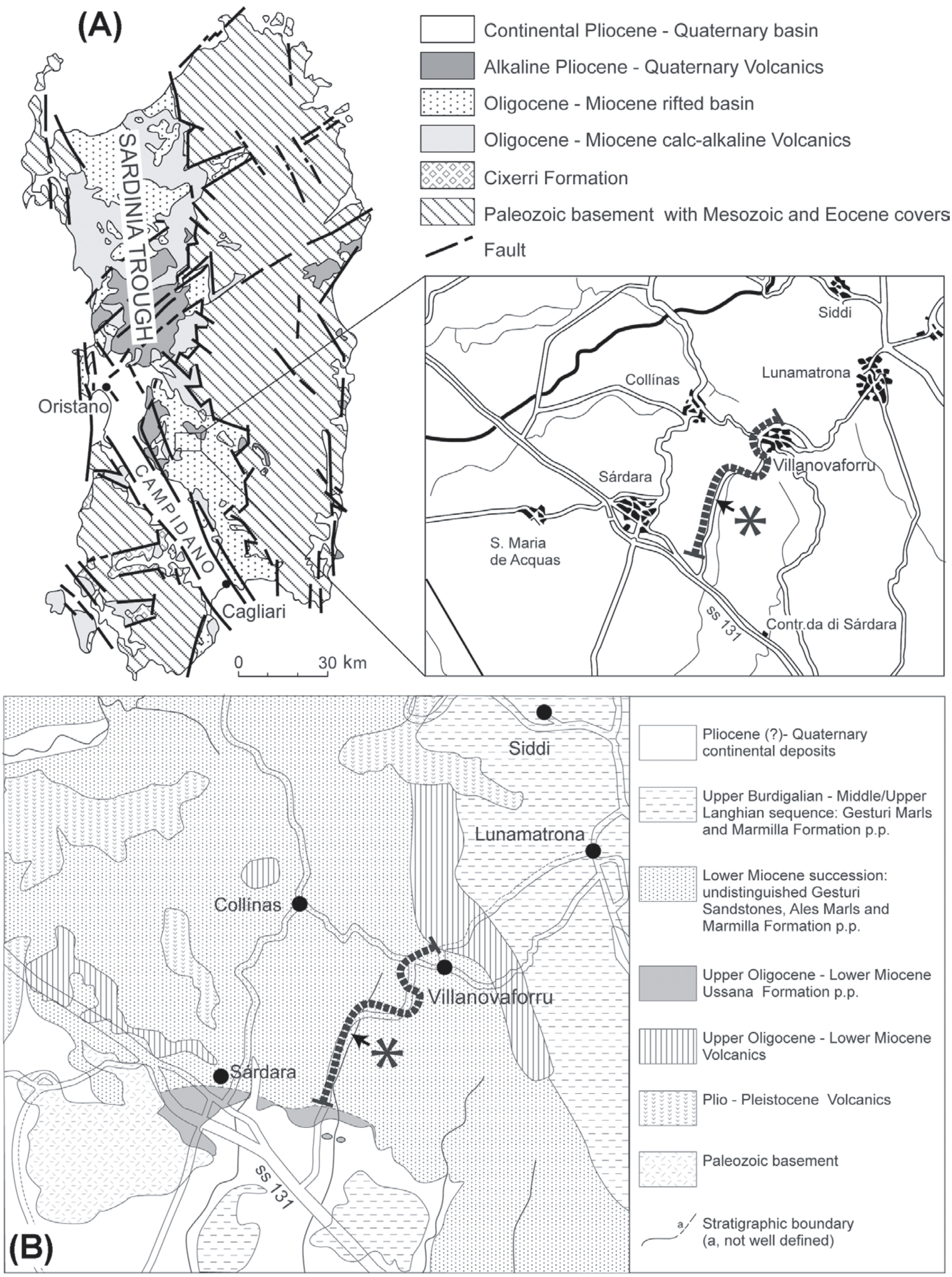

Fig. 1. Geological sketch of Sardinia (after Cherchi & Montadert 1984; modified) (A); schematic geological map of the Villanovaforru area (B). Asterisc (*) indicates the location of the studied stratigraphic section.

tailed integrated stratigraphic analysis represents the most useful correlation method; the study and correlation of the stratigraphic successions may give important information about the development of the "Sardinia Trough" since the Early Miocene.

In this paper we give a detailed stratigraphic characterization of the volcano-sedimentary succession cropping out in the Villanovaforru area (Fig. 1), which can be considered representative of the most important depositional area of the southern sector of the "Sardinia Trough" known as the "Marmilla Basin" (Fig. 2). The reconstructed stratigraphic column (ca. 650 m thick, Fig. 3) provides detailed information about the different volcanic and sedimentary processes.

The Miocene sedimentation in the different depositional areas of the "Sardinia Trough" was strongly influenced by contemporaneous tectonic activity, which was also associated with a wide calc-alkaline basic to acid volcanism (Cherchi & Montadert 1982; Cherchi 1985; Assorgia et al. 1997b, and references therein) as testified by the widespread volcanic and volcanogenic materials interbedded within the sedimentary successions. The complex Neogene geodynamic evolution of Western Sardinia is outlined by different sedimentary cycles, which are separated by unconformity surfaces and by coeval widespread volcanic events (Assorgia et al. 1997b). These authors recognized four main sedimentary cycles: a Lower Oligocene–Middle-Upper Burdigalian cycle; an Upper Burdigalian–Middle-Upper Serravallian cycle; an Upper Serravallian –Lower Messinian cycle; a Pliocene cycle. During marine sedimentation, two main Cenozoic volcanic events (Oligocene-Miocene and Pliocene-Pleistocene) are also recognizable (Assorgia et al. 1997b). The oldest one is calc-alkaline in nature and it may be further subdivided into four minor events:

1 — Lower Basic-Intermediate Lavic Series (LBLS): Oligocene (33/28–23 Ma);

2 — Lower Acid-Intermediate Explosive Series (LAES): Aquitanian (23–20 Ma);

3 — Upper Basic-Intermediate Lavic Series (UBLS): Burdigalian (19–16 Ma);

4 — Upper Acid-Intermediate Explosive Series (UAES): Upper Burdigalian-Serravallian *pro parte* (17–13 Ma).

The studied Burdigalian Villanovaforru volcano-sedimentary succession can be referred to the oldest sedimentary cycle defined by Assorgia et al. (1997b). This succession contains abundant volcaniclastic materials and primary lava flows which can be related to the UBLS defined by the same authors.

Stratigraphy

Owing to its complex tectonic evolution, the sedimentation in the "Sardinia Trough" results in a marked lateral and vertical lithofacies variability and it does not allow an easy correlation of the geological events, also at the scale of the single minor basin. A good example of this variability is represented by the Burdigalian stratigraphic evolution of the "Lugodoro Basin" (northern part of the "Sardinia Trough"; Funedda et al. 2000), which is completely different from that of the coeval "Marmilla Basin" (central-southern "Sardinia Trough").

According to previous authors the stratigraphic succession of the "Marmilla Basin" is characterized by the following, mostly partially heteropic, formations: Ussana Formation, Ales Marls, Gesturi Sandstones, Isili Limestones and Marmilla Formation. (Fig. 2). The stratigraphic units recognized in the "Marmilla Basin" and their stratigraphic relationships are here briefly described.

The marine transgressive cycle, including the studied Villanovaforru volcano-sedimentary succession, overlies the up-

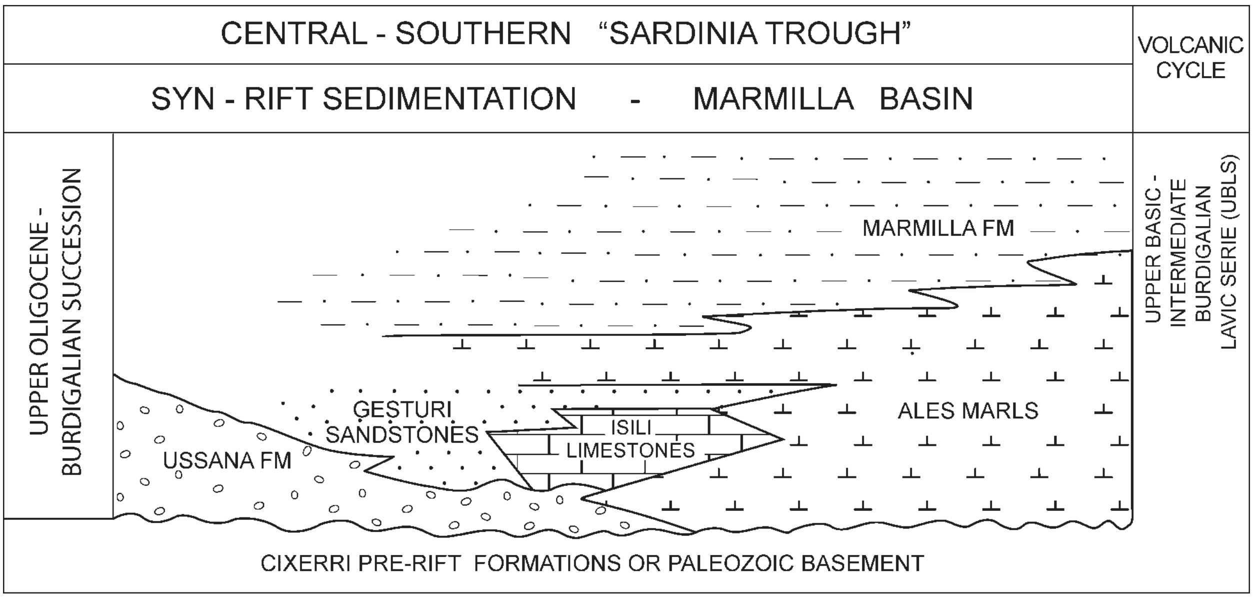

Fig. 2. Stratigraphic relationships of the main sedimentary units of the "Marmilla Basin" in the central-southern "Sardinia Trough" (from Cherchi 1985; Assorgia et al. 1997b). Sedimentary environments: Ussana Formation, continental to littoral; Gesturi Sandstones, shallow-water marine deposits; Isili Limestones, carbonate platform; Ales Marls and Marmilla Formation, littoral to pelagic.

per Oligocene-Aquitanian Ussana Formation (Pecorini & Pomesano Cherchi 1969). This formation is constituted by clastic deposits (ruditic and reddish silty-arenitic beds) with varying thickness, indicating upward a transition from a continental (fan and alluvial plain system) to a marine littoral environment (Cherchi 1985; Assorgia et al. 1997b). The Gesturi Sandstones, which represent the first shallow marine sandy deposition, unconformably lie above the Ussana Formation. They are heteropic with the Isili Limestones, which represent a carbonate platform unit laterally grading also into the Ales Marls. The Marmilla Formation overlies the Ales Marls but it can also rest directly above the Ussana Formation and the Gesturi Sandstones. All the described formations are considered the result of a syn-rift deposition by Cherchi (1985). In the adjacent sectors of the "Sardinia Trough" other units are comprised within the same cycle (Assorgia et al. 1997b). In the marine succession volcanic (primary) products and more frequently volcanogenic (secondary) materials are locally interbedded in different stratigraphic intervals.

A stratigraphic log (about 650 m thick) of the volcano-sedimentary succession cropping out SW of Villanovaforru village (Figs. 1 and 3) has been reconstructed. According to literature in this area the succession consists of the following stratigraphic units (from the base): a) uppermost part of the Ussana Formation *auctorum*, cropping out at the base of the reconstructed log; b) the heteropic Gesturi Sandstones (*auct.*) and Ales Marls *auct.*, lying above the Ussana Formation in the lower part of the log; c) the Marmilla Formation *auct.*, characterizing the middle-upper part of the log. However, the boundaries among these formations are not well recognizable in the measured section. It has been possible to recognize only the top of the Ussana Formation, which has been observed in a little outcrop below the marine succession (Figs. 1 and 3) and probably a part of the Ales Marls, in the lower part of the same. In this way, the studied stratigraphic interval represents a characteristic sedimentation that corresponds to the literature formations. Moreover, the "Marmilla Basin" depositional style was also strongly influenced by contemporaneous explosive and effusive volcanism during the UBLS of Assorgia et al. (1997b); the high abundance of the related volcanogenic materials contributes to the origin of a variety of facies which are not easily correlable with those of the other formations recognized in the surrounding areas. Nevertheless, it cannot be excluded that some stratigraphic intervals, especially those characterized by evident marker beds, could be recognized in all of the other sectors of the "Marmilla Basin". In this case, they can represent an important tool to understand the evolution of the whole "Sardinia Trough" depositional system.

The Villanovaforru succession has been analysed from the lithostratigraphic, sedimentological and biostratigraphic points of view. Although it is not possible to arrange the different lithofacies according to the stratigraphic units defined in literature, the outcrop-scale observations allow us to distinguish some intervals which may be referred as local members, whose lateral extension is still to be verified. This subdivision is particularly useful because of the peculiar characters of the different lithofacies assemblages and, especially, because the unit boundaries recorded in the literature are not recognizable in the field for the examined succession.

Lithostratigraphy

The volcano-sedimentary succession of the Villanovaforru area widely crops out along the road linking the SS N. 131 "Carlo Felice" to Villanovaforru village (Fig. 1). The study of this succession allowed us to reconstruct a stratigraphic section about 650 m thick. The succession shows a constant geometrical setting with layers uniformely dipping towards the north-east; however, the presence of several often syn-sedimentary faults which have been recognized in the surrounding areas (e.g. Collinas village; Cipollari & Cosentino 1997) and the covered intervals does not allow us to exclude the presence of faults. On the other hand, some minor faults have been pointed out as shown in Fig. 3. In spite of this, the biostratigraphic results testify to a continuous sedimentation and this leads us to consider as not remarkable the possible faults affecting the studied stratigraphic section.

The studied Villanovaforru succession (Fig. 3) is made up of generally well-layered lithofacies with dominant medium- to coarse-grained volcanogenic sandstones and subordinate silicified marls with highly variable amounts of volcanic material (Figs. 4 and 5). Marls, calcareous marls, siltstones and marly limestones also occur, always with various amounts of volcanic material and often with abundant foraminifers. Subordinate microconglomerates are also present in the middle-upper part of the succession. Occasionally, thin volcaniclastic beds such as bentonitic, "diatomaceous-tripolaceous" and ochraceous layers occur, whereas some intervals are characterized by high concentrations of vegetable and bivalve remains forming characteristic beds. Subacqueous basaltic lava flows have also been recognized in the middle-lower part of the succession, already defined as high-Mg basalts with tholeiitic affinity by Mattioli et al. (2000).

The dominant volcaniclastic sandstones consist of three lithofacies corresponding to distinct depositional and/or eruptive events.

Lithofacies A, represented by medium- to thick-bedded (20 to 50 cm thick) lithic-rich volcanogenic sandstones with fine- to coarse-grained laminae (5 to 10 mm thick). This lithofacies contains dense volcanic lithic grains of pilotaxitic basalt and porphyric andesite, angular to subangular crystal fragments of plagioclase and subordinate amphibole, clinopyroxene and pumice. Grain-size ranges from 0.2 to 10 mm. Lithofacies A is framework-supported and matrix-poor.

Lithofacies B, consists of thin bedded (5 to 20 cm) vitric-rich volcanogenic sandstones with parallel lamination (2 to 10 mm thick) and subordinate undulose bedding. Its framework composition is made up by comparable proportions of vitric shards and basaltic-andesitic lithic grains and minor amounts of euhedral plagioclase, pyroxene, amphibole and biotite crystals. The vitric component includes pumice fragments and glass shards. Grain size ranges from 0.1 to 2 mm.

Lithofacies C, consists of distinctive darker layers of crystal-rich volcanogenic sandstones (4 to 15 cm thick) with parallel lamination well-defined by biotite flakes and grain size variations. Grain-size ranges from coarse to fine sand, from the bottom to the top, up to laminated and yellow-grey siltstones. This lithofacies contains very abundant framework grains of plagioclase, clinopyroxene and amphibole crystals,

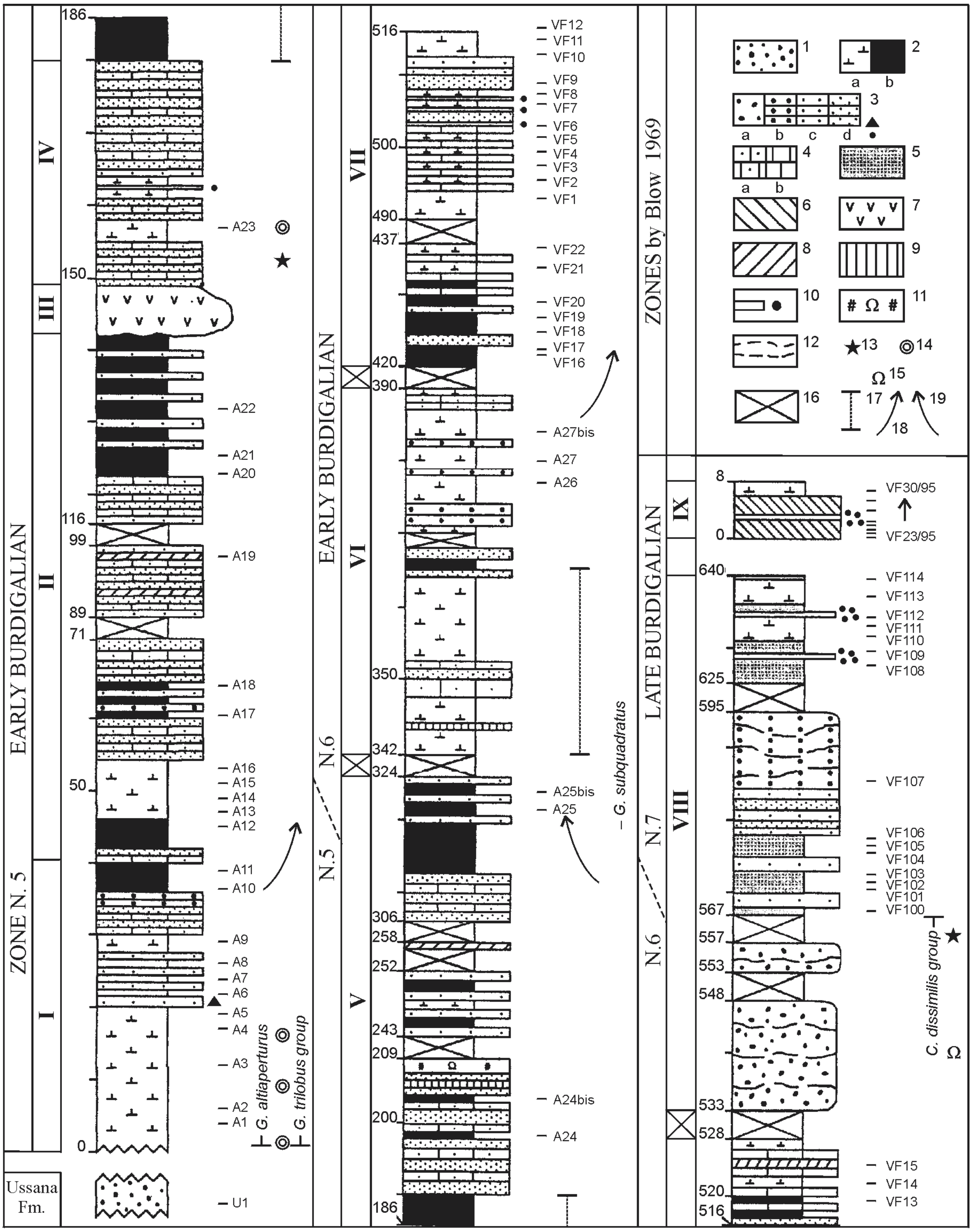

Fig. 3. Stratigraphy of the volcano-sedimentary succession of the Villanovaforru area showing the nine identified lithostratigraphic intervals (roman numbers), collected samples and chronostratigraphy. See text for further details about petrographic features of the volcaniclastic sandstones. **1** — Sandy and conglomeratic deposits of continental and transitional environment (Ussana Formation); **2a** — marls with varying amounts of volcaniclastic materials and subordinate foraminifer-rich beds; **2b** — silicified marls; **3a** — microconglomerates; **3b** — coarse-grained sandstones; **3c** — fine-grained sandstones and rare siltstones with volcaniclastic material; **3d** — thin volcanic epiclastic layers; **3e** — "reddish" sandstone level; **4a** — marly limestones and silicified calcareous marls; **4b** — silicified limestones; **5** — partially silicified marls containing thin volcaniclastic siltstones and sandstones; **6** — thin fine- and medium-grained sandstones (rarely coarse-grained) with interbedded bentonitic layers; **7** — interval with basaltic pillow lavas; **8** — "diatomaceous-tripolaceous" levels; **9** — bentonitic levels; **10** — "ochraceous" levels; **11** — layers with vegetable remnants and small bivalves; **12** — discontinuous/undulating bedding; **13** — faults; **14** — vegetable remnants; **15** — bivalves; **16** — unexposed; **17** — partially exposed; **18** — deepening; **19** — shallowing.

Fig. 4.

with lesser amounts of pumice, lithic grains of pilotaxitic and scoriaceous basalt, andesite and trachyte.

On the basis of lithostratigraphy and petrographic characters nine peculiar intervals (Fig. 3) have been recognized within the volcano-sedimentary succession of the Villanovaforru area. However, preliminary field observations carried out in different areas of the central-southern sector of the "Sardinia Trough" suggest that the recognized intervals should still be regarded as local members which may be connected to vertical facies evolutions.

A summary of the nine stratigraphic intervals features is reported in Table 1. It is worth noting that all the intervals are characterized by a variable amount of volcanogenic materials. In particular, volcanogenic marls with subordinate lithic-rich volcanogenic sandstones characterize ***Interval I***, whereas silicified marls with crystal-rich volcanogenic sandstones and marly limestones are the main lithotypes of ***Intervals II, V*** and ***VII***. ***Interval III*** corresponds to the only primary volcanics (prevailing basaltic pillow lavas) recognized in this area. The **Intervals IV, VI** and **IX** are characterized mainly by vitric-rich volcanogenic sandstones with minor amount of marly limestones and bentonites. Lithic-rich volcanogenic sandstones and microconclomerates with silicified marls are the prevailing lithotypes of ***Interval XIII***.

Table 1: Summary of lithological features of the recognized stratigraphic intervals.

Stratigraphic Interval	Summary description	Thickness (m)
IX	VVS with subordinate bentonites	> 8
VIII	LVS and microconglomerate with silicified marls	107
VII	silicified calcareous marls with CVS	108
VI	marls with subordinate limestones and VVS	48
V	silicified and calcareous marls with CVS	144
IV	VVS with marly limestones	31
III	primary volcanics (prevailing basaltic pillow lavas)	7
II	silicified marls with CVS and marly limestones	112
I	volcanogenic marls with subordinate LVS	30

LVS — lithic-rich volcanogenic sandstones; VVS — vitric-rich volcano-genic sandstones; CVS — crystal-rich volcanogenic sandstones

Fig. 4. Representative lithofacies of the lower part (**Intervals I–III**) of the volcano-sedimentary succession of the Villanovaforru area. **a** — Sandy and conglomeratic deposits of the top of the Ussana Formation; **b** — view of the lower portion of the Villanovaforru succession; **c** — reddish sandstone level in the lower part of **Interval I**; **d** — marls of the lower part of the succession (**Interval II**); **e** — volcaniclastic beds in the lower part of the succession (**Interval II**); **f** — silicified marly limestones in the lower part of the succession (**Interval II**) interbedded with volcanic epiclastic and "diatomaceous" levels; **g)** view of **Interval III** containing basaltic pillow lavas; **h** — and **i** — pillow lava with multiple-rind structures.

Biostratigraphy

New biostratigraphic data from the lower part of the Villanovaforru succession indicate an age comparable to that pointed out in the same area for the "Marmilla Formation" ("Sardara-Villanovaforru succession" of Iaccarino et al. 1984). However, the different scale of observations does not allow us detailed litho- and biostratigraphic correlations between our reconstructed succession and the stratigraphic section of these authors, which also appears to be highly simplified. As an example, Iaccarino et al. (1984) describe the Sardara-Villanovaforru succession as only constituted by marls with interbedded tuffitic layers.

Starting from the base of the studied succession (lower levels of ***Interval I,*** sample A1; Fig. 3), the planktonic foraminiferal assemblages (Table 2) containing *Globigerinoides altiaperturus* Bolli and *Globigerinoides trilobus* (Reus), are evidence that they belong to N5 Zone (Blow 1969) or to a younger interval. Among the samples from these basal levels, there are no other components that might provide greater biostratigraphic precision, except for the presence of *Globigerina venezuelana* Hedberg. This species does not seem to exist beyond the top of N6 Zone, although some authors extended its presence up to considerably higher levels (Kennett & Srinivasan 1983; Bolli & Saunders 1985). Also noteworthy is the absence of *Globigerinoides subquadratus* Brönnimann and of *Globorotalia praescitula* Blow in these levels, which could indicate that they were deposited before the levels in which they currently appear, close to the base of N6 Zone. The absence of typical specimens of *Catapsydrax dissimilis* (Cushman et Bermúdez) is noteworthy, though we have observed examples of a morphology similar to *C. dissimilis* or *Catapsydrax unicavus* Bolli, Loeblich et Tappan in which "bulla" have not developed. This component is frequently encountered in the hemipelagic marine deposits of the lower Miocene prior to N7 Zone. Iaccarino et al. (1984) have also noted this fact, suggesting that the absence of *Catapsydrax* may be due to the shallowness of the environment. However, the composition of the microfauna seems to indicate there is sufficient depth for *C. dissimilis* to develop, at least in most of the section.

At higher levels (***Intervals I*** to ***V***) the succession still contains very similar assemblages of planktonic foraminifers. Noteworthy among the differences here is the appearance of isolated specimens of *Globigerina tripartita* Koch (sample A5), some atypical specimens of *C. unicavus* (samples A18, A21 and A22) and *Globigerinoides* with three chambers in the final whorl and a single dorsal aperture (samples A6 to A24), which could be considered transition forms between *G. altiaperturus* and *G. subquadratus* (in Table 2 these are referred to as cf. *G. subquadratus*).

At the highest levels of ***Interval V*** (samples A25 and A25bis) typical specimens of *G. subquadratus* appear. The first appearance datum (FAD) of *G. subquadratus* seems to be close to that of *Globigerinatella insueta* Cushman et Stainforth (zonal marker of the base of N6 Zone) although this latter species is very rare in the Mediterranean domain and it has

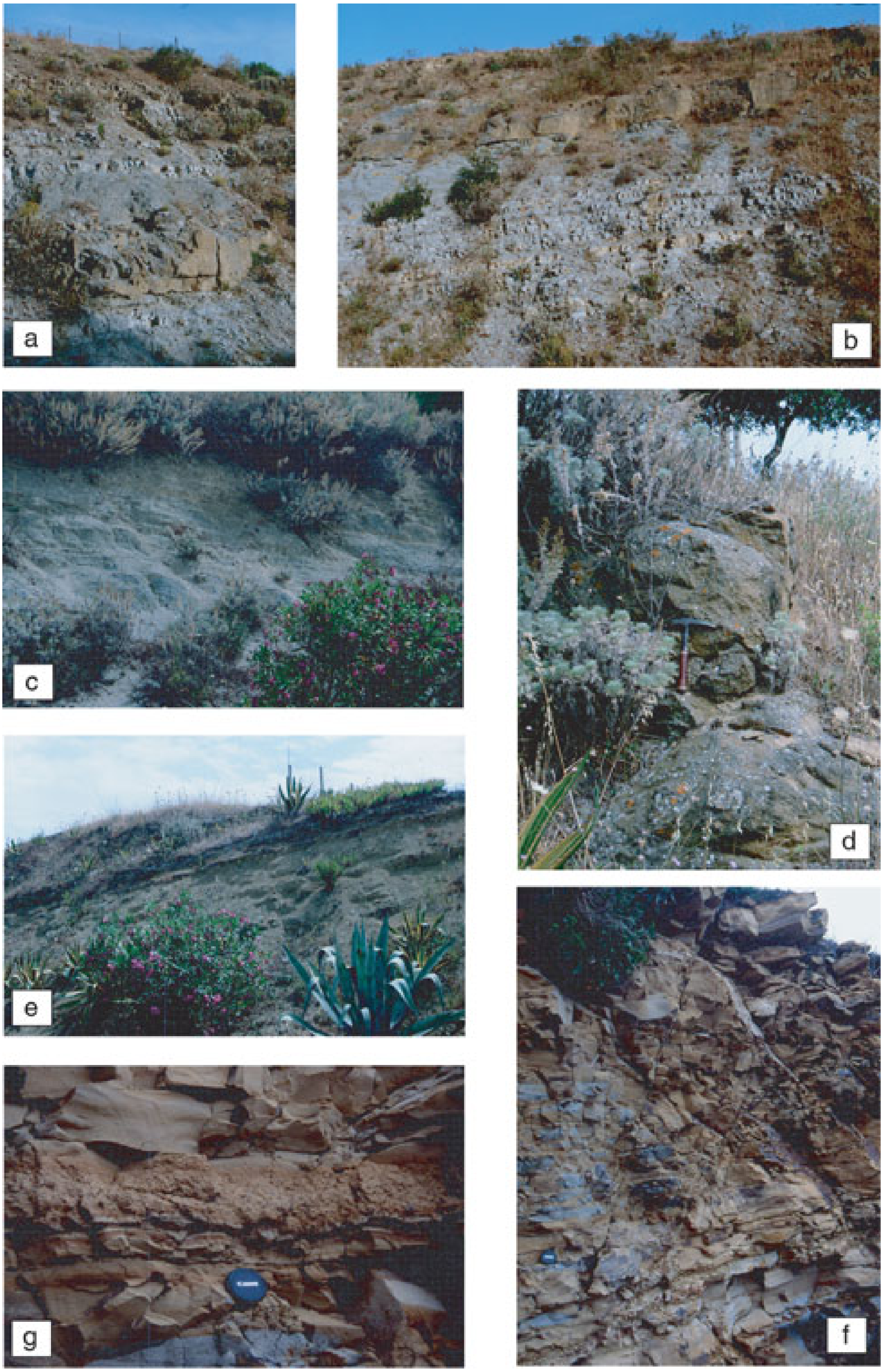

Fig. 5.

not been found in this succession. Some specimens of *C. dissimilis* (sample A25) and *C. unicavus* (sample A27bis from ***Interval VI***) have also been observed. The presence of these species shows that this part of the succession still lies below N7 Zone.

According to the zonation of Iaccarino (1985), established for the Mediterranean domain, ***Intervals I–VI*** belong to the zone of *Globigerinoides altiaperturus–Catapsydrax dissimilis*. According to the zonal scheme of Molina (1979) the subzone of *G. altiaperturus* and the lower part of the *G. subquadratus* Subzone are distinguished.

Above ***Interval VI*** the microfauna is poorly preserved. In ***Interval VII*** (samples VF16 to VF22 and VF1 to VF15) *G. trilobus, G. altiaperturus, G. subquadratus* (very scarce), *G. venezuelana, G. tripartita, Globorotaloides suteri* Bolli and atypical specimens of *C. dissimilis* are still present. Thus, ***Interval VII*** belongs to the same biostratigraphic interval as the upper levels of ***Interval V*** and those of ***Interval VI*** (N6 Zone, Blow 1969; or the upper part of the zone of *G. altiaperturus–C. dissimilis*, Iaccarino 1985).

The middle-upper part of ***Interval VIII*** (samples VF100 to VF114) contains scarce and poorly preserved planktonic foraminifers. In the assemblages we have noted the absence of the species that disappear at the top of N6 Zone (*C. dissimilis, C. unicavus, G. suteri* and the *G. venezuelana* group, Blow 1969). This seems to suggest that the middle-upper part of ***Interval VIII*** belongs to N7 Zone (Blow 1969; or *G. trilobus* Zone, Iaccarino 1985); however, some doubt still remain due to the poor preservation of the microfauna.

In the highest part of the succession corresponding to ***Interval IX*** (samples VF23 to VF30) *C. dissimilis* and other species indicating the N6 Zone are absent, while specimens of the *G. trilobus* group with a strongly embracing final chamber appear, which can be assigned to *Globigerinoides bisphaericus* Todd. These assemblages seem to indicate that the uppermost part of the succession corresponds to the N7 Zone (Blow 1969). Nevertheless, we did not detect the predominance of *Globoquadrina* and of *G. trilobus* group, which usually characterize the higher part of the N7 Zone in the Mediterranean domain.

Chronostratigraphy

In the bio-chronostratigraphical correlation used by many authors working in the Mediterranean domain (Demarcq et al. 1974; Molina 1979; Iaccarino 1985) the Aquitanian-Burdigalian boundary is placed at the FAD of *Globigerinoides altiaperturus*. Thus, the upper Aquitanian could be characterized by assemblages without *G. altiaperturus*, but including *G. dehiscens* and little-evolved morphotypes of the *G. trilobus* group, mainly *G. quadrilobatus* and *G. inmaturus* forms.

The Burdigalian would lie between the *FAD* of *G. altiaperturus* and that of *Praeorbulina,* and could be divided into two parts, separated by the last occurrence datum (*LOD*) of *C. dissimilis* (e.g. Serrano 1992). The Lower Burdigalian would be characterized by the joint presence of *G. altiaperturus* and *C. dissimilis.* This biostratigraphic interval has frequently been used in the Mediterranean domain (Bizon & Bizon 1972; Cita 1976; Bizon 1979; Molina 1979; Iaccarino & Salvatorini 1982; Iaccarino 1985) and corresponds to part of N5 and the whole of the N6 Zone (Blow 1969). Within this interval Molina (1979) distinguishes two subzones limited by the FAD of *G. subquadratus.* The Upper Burdigalian is limited to the N7 Zone (Blow 1969), between the LAD of *C. dissimilis* and the FAD of *Praeorbulina*. In the upper part of this interval, the assemblages are frequently dominated by *Globoquadrina* and the *G. trilobus* group, with abundant specimens of the *G. bisphaericus* morphotype.

According to this bio-chronostratigraphic correlation, the succession comprising ***Intervals I–VI*** was completely deposited during the Early Burdigalian. From the level corresponding to sample A25 (upper part of ***Interval V***), in which the first specimens of *G. subquadratus* appear, deposition occurred during the upper part of the Early Burdigalian (Fig. 3).

Interval VII was also deposited in the upper part of the Early Burdigalian. Above this interval, the transition to the Late Burdigalian cannot be accurately identified, but it seems likely that starting from sample VF100 (***Interval VIII***) the Late Burdigalian occurs (Fig. 3).

Fig. 5. Representative lithofacies of the intermediate-upper part (**Intervals IV–IX**) of the volcano-sedimentary succession of the Villanovaforru area. **a** — and **b** — silicified calcareous marls including frequent volcaniclastic beds (**Interval VII**); **c** — partially silicified marls containing thin volcaniclastic siltstones and arenites (lower part of **Interval VIII**); **d** — coarse-grained arenite beds (**Interval VIII**); **e** — arenites and marls of the upper part of **Interval VIII**; **f** — arenites with interbedded bentonite layers and thin microconglomeratic levels (**Interval IX**) with a detail **g**.

Sedimentary environment

Most of the samples collected in ***Intervals I–VI*** (A1 to A27bis) contain abundant microfauna sufficiently well preserved to enable precise identification. In the 125 μm fraction the microfauna mainly comprises planktonic foraminifers, although the relative abundance varies within the succession.

In the basal levels (samples A1 to A4; Fig. 3) the relative abundance of planktonic foraminifers ranges from 60 to 70 %. The accompanying benthic microfauna is mainly composed of *Florilus* (only in the first level), *Lenticulina, Heterolepa, Nodosaria* and abundant radioles of Echinoidea. These assemblages are characteristic of upper bathyal hemipelagic deposits.

Above samples A7 and A9, where no microfauna are present, the predominance of the planktonic foraminifers becomes even more pronounced, exceeding 90 % of all the microfauna present; only in few layers (e.g. sample A13) the planktonic foraminifers are scarce and show traces of dissolution, while radiolarians are found in greater numbers. These deposits seem to reflect a deepening of the basin, coincident with intra-basinal volcanic activity related to extensional faulting.

The upper levels of ***Interval V*** and those of ***Interval VI*** (samples A25 to A27bis) show somewhat lower abundances of planktonic foraminifers (around 75 %), with a varied

Table 2: Distribution and relative abundance of planktonic foraminifers in the recognized stratigraphic intervals. The corresponding zones and age are also indicated.

Stratigraphic intervals	Samples	Relative abundance					Planktonic Foraminifers																												ZONES	AGE
		Planktonic foraminifers	Calc. benthic foraminifers	Agglutinated foraminifers	Radiolarians	Other groups	*Globigerina tripartita* Koch	*Globigerina venezuelana* Hedberg	*Globigerina angustiumbilicata* Bolli	*Globigerina praebulloides* Blow	*Globigerina falconensis* Blow	*Globigerina woodi* Jenkins	*Globigerina connecta* Jenkins	*Globigerinoides parawoodi* Keller	*Globigerinoides altiaperturus* Bolli	*Globigerinoides subquadratus* Brönnim	*Globigerinoides* gr *trilobus* (Reuss)	*Globigerinoides bisphaericus* Todd	*Globigerinella obesa* (Bolli)	*Neogloboquadrina nana* (Bolli)	*Neogloboquadrina continuosa* (Blow)	*Neogloboquadrina siakensis* (LeRoy)	*Neogloboquadrina acrostoma* (Wezel)	*Globorotalia peripheroronda* Bl&Ban	*Globorotalia zealandica* Hornibrook	*Globorotalia praescitula* Blow	*Globigerinita juvenilis* (Bolli)	*Globigerinita naparimaensis* Brönnim	*Turborotalita quinqueloba* (Natland)	*Globoquadrina globosa* Bolli	*Globoquadrina baroemoenensis* (LRoy)	*Globorotaloides suteri* Bolli	*Catapsydrax unicavus* B Loeb&Tap	*Catapsydrax dissimilis* (Cush&Berm)		
IX	V30	▮	❘	·	◘	·				o									o																N 7	LATE BURDIGALIAN
	V28	●	▮	·	▮	▮			o	o	o	o					o		o		o										o					
	V27	◘	❘	·	▮	·			o	o	o	o					o		o			o									o					
	V26	▮	·	·	◘	·				o	o	o										o														
	V24	●	▮	·	▮	▮				o		o			o		o				o			o							o					
	V23	◘	❘	·	▮	·				o	o	o		o			o	o	o		o	o	o					o			o					
VIII	V114									o																					o					
	V113								o												o															
	V112	●	▮	❘	▮	❘			o	o		o			o				o			o									o					
	V111									o																					o					
	V110									o																										
	V109								o	o		o					o					o									o					
	V107																					o														
	V103									o												o														
	V101									o																										
	V100								o	o		o			o	o	o				o										o				/	/
VII	V15	◘	❘	·	❘	·			o	o		o	o	o			o		o			o	o			o		o			o	o		o	N 6	EARLY BURDIGALIAN
	V14	◘	·	❘	▮	·		o				o		o																	o			o		
	V13	◘	❘	·	·	·		o		o		o			o		o					o									o		o	o		
	V11	◘	❘	❘	·	·		o		o		o		o			o		o			o												o		
	V10	■	❘	❘	·	·				o		o							o		o							o			o					
	V7	●	▮	❘	▮	·				o		o																			o					
	V6	●	▮	❘	●	·				o		o					o														o					
	V5	●	❘	❘	▮	❘				o		o					o														o					
	V4	◘	❘	·	❘	·			o	o		o	o	o		o	o		o		o	o	o								o					
	V2	◘	❘	❘	❘	❘	o	o		o		o			o		o	o			o	o	o				o	o			o			o		
	V1	■	·	·	·	·		o		o		o			o		o		o	o	o	o	o								o	o		o		
	V22	◘	❘	·	❘	·				o	o	o			o		o					o														
	V21	◘	❘	·	❘	·		o		o		o			o		o		o		o	o						o			o					
	V20	●	▮	·	●	❘		o		o		o					o				o	o														
	V19	◘	❘	❘	▮	❘		o		o											o	o	o								o	o				
	V18	◘	❘	·	❘	·		o	o	o		o	o		o	o	o		o	o		o		o				o				o	o	o		
	V16	●	❘	❘	▮	·	o	o		o		o	o				o			o		o														
VI	A27b	◘	▮	·	·	·		o	o	o		o			o	o	o		o			o								o	o		o			
	A27	●	▮	▮	❘	·			o	o		o	o		o	o	o				o	o						o						o		
	A26									o		o			o		o				o	o														
V	A25b	◘	▮	·	❘	·		o	o	o		o			o	o	o		o		o	o		o				o	o		o				/	
	A25	■	·	·	·	·		o	o	o		o			o	o	o		o		o	o									o			o	N 5 (UPPER PART)	
	A24b	■	❘	·	·	·		o		o		o			o	o	o																			
	A24	◘	▮	❘	·	·				o							o					o									o					
IV	A23									o																										
III																																				
II	A22	◘	▮	·	·	❘		o		o		o					o			o	o	o			o					o			o			
	A21	■	·	·	·	·		o	o	o		o	o		o	o	o		o		o	o								o			o			
	A20	■	❘	·	·	·		o		o		o													o					o						
	A19	■	❘	·	·	·		o		o		o			o		o					o			o			o		o						
	A18	■	·	·	·	·		o	o	o		o			o		o	o	o			o						o		o			o			
	A17	■	·	·	·	·		o	o	o		o		o	o		o		o			o						o	o	o						
	A16	■	·	·	❘	·			o	o		o										o								o						
	A15	■	·	·	·	·		o	o	o		o			o	o	o		o		o	o		o						o						
	A14	■	·	·	·	·		o	o	o		o		o	o	o	o		o		o	o		o				o		o						
	A13	●	▮	·	●	·			o	o		o	o				o		o	o		o														
	A12	■	·	·	·	·		o	o	o			o				o		o			o														
	A11	◘	▮	·	·	·			o	o		o			o					o	o	o														
	A10	◘	❘	·	·	·		o	o	o												o														
I	A6	■	·	·	·	❘		o	o	o		o			o	o	o		o		o	o			o		o			o						
	A5	◘	❘	·	·	❘	o	o	o	o		o		o	o		o		o	o	o	o								o						
	A4	◘	▮	·	·	❘		o	o	o		o		o	o		o		o	o	o	o														
	A3	◘	▮	·	·	❘		o	o	o		o	o		o		o		o	o	o	o								o						
	A2	●	▮	·	·	▮		o	o	o		o	o		o		o		o	o	o	o								o						
	A1	◘	▮	·	·	▮		o	o	o		o	o	o	o		o		o			o								o						

■ >90% ◘ 90-66% ● 66-33% ▮ 33-10% ❘ 10-3% · <3%

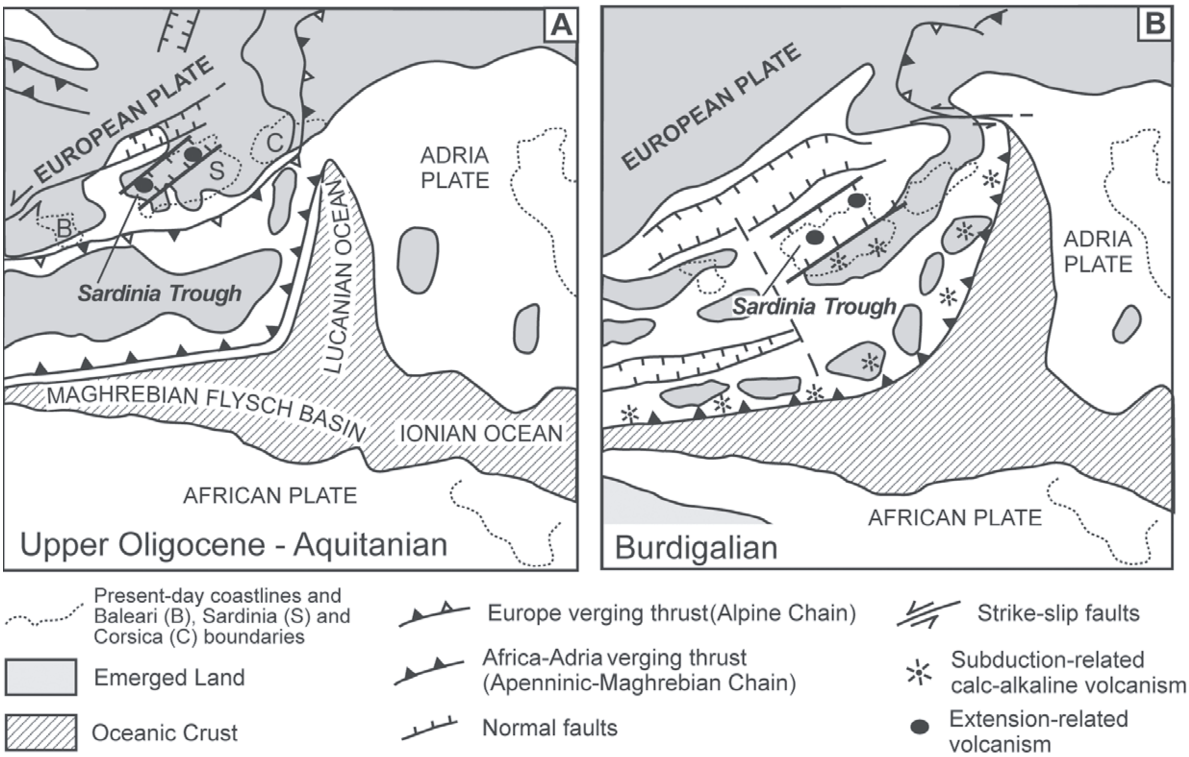

Fig. 6. Paleogeographic and paleotectonic evolutional sketch of the Sardinia-Corsica Block during the Late Oligocene-Early Miocene (from de Capoa et al. 2002, modified) with the location of the "Sardinia Trough".

benthic assemblage including *Nodosaria, Lenticulina, Heterolepa, Cibicides, Bulimina, Oridorsalis, Nonion* and *Pullenia*, in addition to remains of Echinoidea. It is likely that these levels reflect a slight shallowing of the basin.

In ***Intervals VII–IX*** the microfauna mainly consists of planktonic foraminifers, usually exceeding 80 %, although in many levels the microfauna is very scarce. Within these intervals radiolarians often exceed 10 %. This group, however, increases considerably in levels where there is evidence of high carbonate dissolution (samples VF112, VF114, VF24 to VF28). Carbonate dissolution could have been facilitated by the intense volcanic activity and a certain degree of confinement of the bottom waters. The remaining constituents of the microfauna are calcareous benthic foraminifers (mainly *Nodosaria* and *Lenticulina*) and agglutinants (e.g. *Reophax, Textularia, Trochammina*).

These observations lead us to conclude that ***Intervals VII*** to ***IX*** must have been deposited in a relatively deep marine environment comparable to the lower part of ***Interval II*** or perhaps somewhat deeper.

Discussion

The Early Miocene geodynamic evolution of Central-Western Sardinia has been investigated by several authors (Coulon 1977; Cherchi & Montadert 1982; Guerrera et al. 1993; Maillard & Mauffret 1993; Carmignani et al. 1995; Vigliotti & Langenheim 1995; Assorgia et al. 1997b; Gattacceca 2001), as well as the whole stratigraphic succession. However, a detailed stratigraphic analysis of the different formations connected with the sedimentation in the "Sardinia Trough" is still undefined. The lack of these data does not allow detailed lithostratigraphic correlations across the basin and makes it difficult to calibrate the different depositional events. Filling this gap, the studied stratigraphic section of the Villanovaforru area can be considered as well representative of the Early Miocene sedimentation in the central-southern sector of the "Sardinia Trough" (Marmilla Basin).

The Villanovaforru succession is dominated by fine- to coarse-grained volcaniclastic deposits whose different lithofacies are related to depositional (mainly epiclastic), diagenetic and alteration processes. The facies recognized in the studied stratigraphic section show differences in thickness and amount of volcanogenic materials which may be explained supposing a complex physiographic setting and source areas characterized by a varying amount, in space and time, of available volcanic materials. This provides an example for the influence, on marine sedimentation, of a coeval volcanism. The coeval volcanic activity is also testified by the presence of high-Mg basaltic pillow lavas interbedded in the lower part of the succession (Mattioli et al. 2000).

The whole studied stratigraphic section extends from the Early to the Late Burdigalian (Zone N5 to N7, Blow 1969) and it seems to be characterized by a continuous sedimentation, without *hiatus* at least at the scale of the biostratigraphic resolution. The deposition is certainly controlled by a strong syn-sedimentary tectonic activity and, on the basis of the litho- and biostratigraphic reconstructions, it is possible to estimate a sedimentation rate of about 200 m/My.

Lithostratigraphic, petrographic and biostratigraphic analyses allowed us to identify and characterize nine stratigraphic intervals (***Intervals I*** to ***IX***), which could represent an important sedimentary record of the overall environmental basin evolution in the "Sardinia Trough". In fact, at the basal levels (lower marly portion of ***Interval I,*** which overlies continental deposits) the microfossil assemblages indicate hemipelagic deposition, corresponding to an upper bathyal environment. Above these levels, a deepening of the basin seems to occur (***II–IV Intervals***, cf. arrow in Fig. 3) and this is probably connected with a climax of the volcanic activity related to extensional faulting. The upper levels of the ***Interval V*** and the ***Interval VI*** reflect a slight shallowing of the basin (cf. arrow in Fig. 3), whereas the ***VII–IX Intervals*** must have been deposited in a relatively deep marine environment, similar to that of the lower part of the ***Interval II***.

According to the collected data, a schematic model of the Late Oligocene–Burdigalian evolution of the Sardinia-Corsica Block is here proposed and the different phases are schematically shown in Fig. 6. A continental deposition (Ussana Formation, not indicated in Fig. 6 for a scale problem), which is Late Oligocene–Aquitanian in age, occurs during the first stages of crustal thinning, before the starting of the drift of the Sardinia-Corsica Block (Fig. 6A). During the Burdigalian, the volcano-sedimentary marine succession of Villanovaforru deposited during the drift towards east of the block and it was strongly influenced by the contemporaneous volcanic activity which occurred in the area of the "Sardinia Trough" (Fig. 6B). In this way, the reconstructed stratigraphic succession comprises the transition from a continental (Fig. 6A) to a marine (Fig. 6B) syn-rift deposition environment and it was deposited during the extensional tectonics which caused the development of the "Sardinia Trough" and its lenghtening towards the north (Rossi et al. 1997). This is in agreement with the extensional deformation suggested by the high-Mg composition of the interbedded basaltic lava flows (Mattioli et al. 2000), which are also similar to those described in the NW "Sardinia Trough" (Morra et al. 1997). These results favour the hypothesis that, during the deposition of the volcano-sedimentary succession of Villanovaforru (Burdigalian *p.p.*), the rifting of the Sardinia-Corsica Block was not yet accomplished.

Conclusion

This study allows us to point out the following main results.

1) The reconstruction of a new detailed stratigraphy of the volcano-sedimentary succession outcropping in the Villanovaforru area, which is considered as representative of the Early Miocene sedimentation within the central-southern sector of the "Sardinia Trough" (Marmilla Basin).

2) The litho- and petrographic descriptions of the fine- to coarse-grained volcaniclastic lithofacies, as well as the characterization of the primary volcanics (basaltic pillow lavas) interbedded in the measured section. This provides a good example for the influence on marine sedimentation of a coeval volcanism.

3) A detailed biostratigraphic analysis of the whole studied succession, which extends from Early to Late Burdigalian without *hiatus* (continuous sedimentation) and is characterized by an estimated sedimentation rate of about 200 m/My.

4) The paleoenvironmental reconstruction of the succession, which reveals a transition from a continental (upper Oligocene-Aquitanian) to a marine (Burdigalian) depositional environment.

5) The presence, in the Burdigalian, of an extensional tectonics which caused the development of the "Sardinia Trough" and a contemporaneous effusive volcanic phase with peculiar basaltic high-Mg composition. This extensional tectonics also suggests that, during the deposition of the volcano-sedimentary succession of Villanovaforru, the rifting of the Sardinia-Corsica Block was still in progress.

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