Geodinamica Acta
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tgda20

The Lower Miocene volcaniclastic sedimentation in the Sicilian sector of the Maghrebian Flysch Basin: geodynamic implications

Paola de Capoa [a], Angelida Di Staso [a], Francesco Guerrera [b], Vincenzo Perrone [b], Mario Tramontana [c] & Mohamed Najib Zaghloul [d]

[a] Dipartimento di Scienze della Terra, Università di Napoli "Federico II", Largo San Marcellino 10, 80138, Naples, Italy

[b] Istituto di Geologia, Università di Urbino, Campus Scientifico, Località Crocicchio, 61029, Urbino, Italy

[c] Istituto di Geodinamica e Sedimentologia, Università di Urbino, Campus Scientifico, Località Crocicchio, 61029, Urbino, Italy

[d] Département des Sciences de la terre et d'Océanologie, Université Abdelmalek Essaadi de Tanger, Morocco

Published online: 30 May 2012.

To cite this article: Paola de Capoa, Angelida Di Staso, Francesco Guerrera, Vincenzo Perrone, Mario Tramontana & Mohamed Najib Zaghloul (2002) The Lower Miocene volcaniclastic sedimentation in the Sicilian sector of the Maghrebian Flysch Basin: geodynamic implications, Geodinamica Acta, 15:2, 141-157

To link to this article: http://dx.doi.org/10.1080/09853111.2002.10510747

ELSEVIER

Geodinamica Acta 15 (2002) 141–157

Geodinamica Acta

www.elsevier.com/locate/geoact

The Lower Miocene volcaniclastic sedimentation in the Sicilian sector of the Maghrebian Flysch Basin: geodynamic implications

Paola de Capoa [a], Angelida Di Staso [a], Francesco Guerrera [b,*], Vincenzo Perrone [b], Mario Tramontana [c], Mohamed Najib Zaghloul [d]

[a]*Dipartimento di Scienze della Terra, Università di Napoli "Federico II", Largo San Marcellino 10, 80138 Naples, Italy*
[b]*Istituto di Geologia, Università di Urbino, Campus Scientifico, Località Crocicchia, 61029 Urbino, Italy*
[c]*Istituto di Geodinamica e Sedimentologia, Università di Urbino, Campus Scientifico, Località Crocicchia, 61029 Urbino, Italy*
[d]*Département des Sciences de la terre et d'Océanologie, Université Abdelmalek Essaadi de Tanger, Morocco*

Received 5 September 2001; accepted 23 February 2002

Abstract

Volcaniclastic debris-rich formations, characterising the Troina–Tusa Unit in the Sicilian Maghrebian Chain, are examined. The Troina–Tusa Unit terrains sedimented in the Maghrebian Flysch Basin, which, from Jurassic to Early Miocene, constituted the southernmost branch of the Western Tethys, located between Africa and the Mesomediterranean Terrane margins. New field, biostratigraphic and petrographic data enable a reconstruction of the palaeogeographic and structural evolution of the Flysch Basin immediately before its deformation. All the studied formations transpired to be Burdigalian in age. The sandstone compositions, showing different source areas (magmatic arc, recycled orogen and continental block), indicate a provenance for the clastic material from a crystalline basement with an active volcanic arc, replaced by a remnant volcanic arc, which was rapidly completely eroded. The source area that has been considered is Sardinia, where Upper Oligocene–Aquitanian calc-alkaline volcanites are widespread, but the sedimentological characteristics and the Burdigalian age do not fit with this provenance. The Burdigalian calc-alkaline arc should be located on the internal side of the Troina–Tusa Basin, above the already stacked Peloritanian units. A migration of the volcanic activity, connected with the subduction plain roll-back, can be envisaged from the Sardinia Block to the Peloritanian Chain, this latter still docked to the Sardinia–Corsica massif. © 2002 Éditions scientifiques et médicales Elsevier SAS. All rights reserved.

Keywords: Volcaniclastic sedimentation; Geodynamics; Early Miocene; Maghrebian Flysch Basin; Sicily

1. Geological setting

The Flysch Basin represents one of the main palaeogeographic domains evidenced across the Alpine Chains of the western Mediterranean. In fact, the Flysch Basin-related terrains have been recognised in the western sector of the Betic Cordilleras, in the whole Maghrebian Chain, between the Gibraltar and the Calabria–Peloritani Arcs [1–4]. The tectonic units resulting from the deformation of this basin are sandwiched between the metamorphic and plutonic terrains of the Internal Domains and the carbonate and pelitic ones of the External Domains (Fig. 1). The continuation towards the northeast of the Flysch Basin across the Southern Apennines, where this palaeogeographic realm has been named Lucanian Ocean [5,6], has been proposed by Guerrera et al. [4] and Bonardi et al. [7].

The Flysch Basin develops starting from the Jurassic as a result of the opening of the Western Tethys [2,4,8]. According to Guerrera et al. [4], it constitutes the southernmost branch of this ocean, located between the African Continental Margin, to the south, and the margin of a microcontinent (Mesomediterranean Terrane), to the north. The deformation of the Flysch Basin occurs during the Early Miocene, and it is accomplished, with the collision between African and European plates, in the Middle Miocene.

* Corresponding author.
E-mail addresses: decapoa@unina.it (P. de Capoa), distaso@unina.it (A. Di Staso), f.guerrera@uniurb.it (F. Guerrera), perrone@uniurb.it (V. Perrone), tramontana@uniurb.it (M. Tramontana), zaghloul@nirvanet.net (M.N. Zaghloul).

PII: S0985-3111(02)01085-9

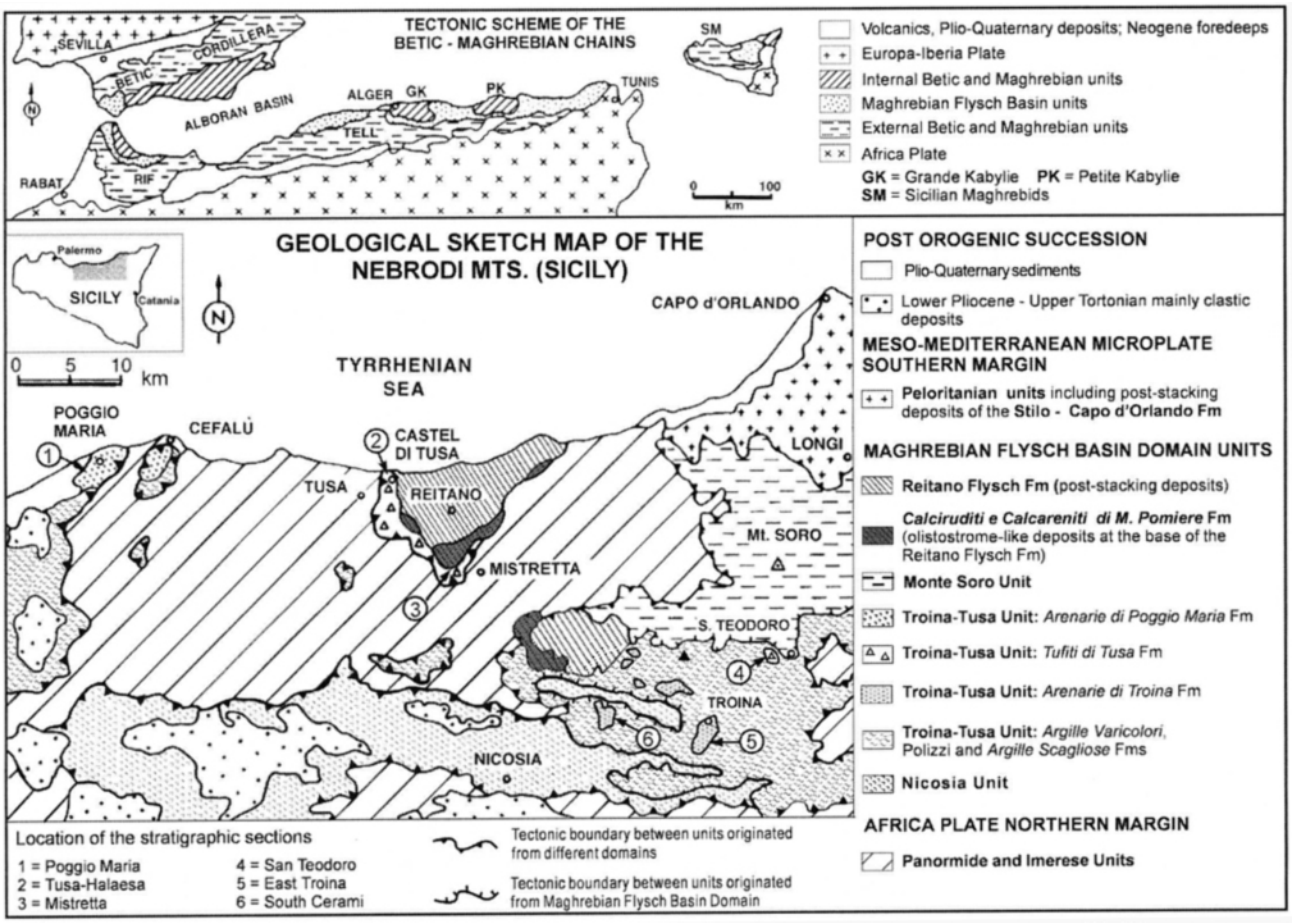

Fig. 1. Tectonic scheme of the Betic and Maghrebian Chains and geological sketch map of the Maghrebian Flysch Basin units in the Nebrodi Mts. (central-northern Sicily). Volcaniclastic formations of the upper part of the Troina–Tusa Unit and location of studied stratigraphic sections are evidenced (1–6).

The oceanic magmatic substratum is only locally preserved in the Calabria–Lucania border area [4,9], Sicily [10], Petite Kabylie [11–15], Grande Kabylie [12] and Rif [10]. The overlying sedimentary succession starts with Late Jurassic–Early Cretaceous lithotypes, which are characteristic of oceanic covers, represented by radiolarites, calcschists and turbiditic sediments. These latter constitute a Tithonian–Neocomian marly–calcareous pre-flysch, which is followed by a thick Hauterivian–Albian arenaceous flysch and finally by Upper Cretaceous (often carbonate) deposits, alternating with minor pelagic sediments. Uniform, mainly pelitic, successions deposited during the Palaeogene–Aquitanian (in Sicily particularly); they are characterised by varicoloured clayey facies, within which a calcareous and marly–calcareous turbiditic formation, reaching up to hundreds of metres in thickness, is interbedded.

In the Early Miocene, in Sicily, and already from the Late Oligocene, in Kabylias and Rif, the onset of the compressive deformation caused a deep modification of the tectonic setting, whose main features were almost unmodified since the Late Jurassic. The sedimentation abruptly changes starting from the northern margin of the basin, and it is characterised by quartz–feldspar–lithic turbidites, constituting a synorogenic flysch fed by the already piled units of the Internal Domains. In the Tellian and Rifian sectors, the flysch successions end with silty marls Burdigalian in age. About the whole magmatic crust is subducted, and only small pieces are stacked in the accretionary wedges of the Maghrebian Chain and Southern Apennines.

During the Langhian, the beginning of the continental collision between the Africa–Adria Margins and the palaeochain, which is docked against the Iberian–European block, is documented in the Sicilian sector of the basin. Here, siliciclastic (Reitano Flysch Fm.) and calcarenitic (Floresta Calcarenites Fm.) deposits suture the Flysch Basin-related nappes and the Antisicilide Complex of Ogniben [16], respectively. This latter is characterised by terrains resulting from the Flysch Basin, which override by means of backthrusting the nappes originated from the Peloritanian Domain. Similarly, in the Southern Apennines, the Lucanian Oceanic nappes are sealed by the Langhian clastic deposits of the Cilento Group. The available data for the Tellian Maghrebids should demonstrate a Latest Burdigalian age for the oldest unconformable deposits, which lie both on the flysch units and on the highest external Tellian units. In the Maghrebian Chain, the deformation continues

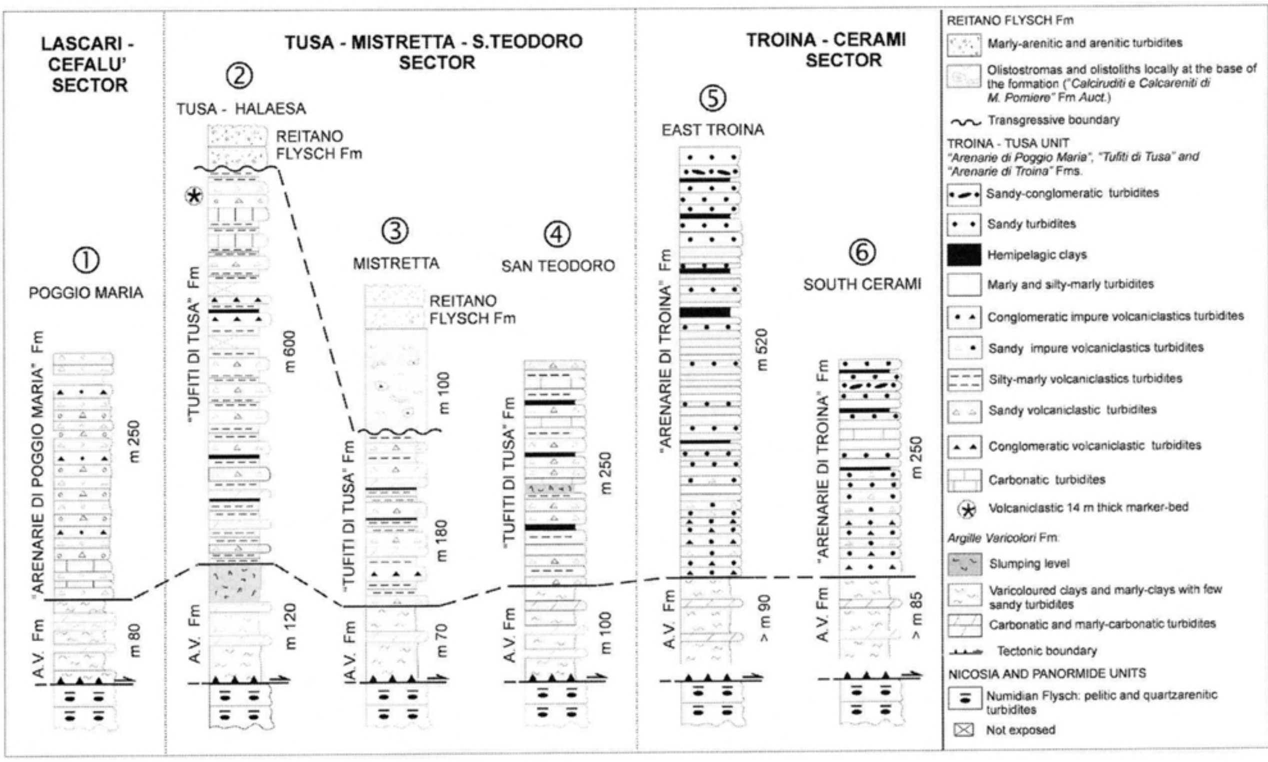

Fig. 2. Representative stratigraphic successions of volcaniclastic formations (*Arenarie di Poggio Maria*, *Tufiti di Tusa* and *Arenarie di Troina*) of the upper interval of the Troina–Tusa Unit.

up to the Pliocene, so originating a thrust and fold belt involving the Meso–Cenozoic covers of the African Margin.

In this framework, which can be assumed from the Gibraltar Arc to the Southern Apennines, it is noteworthy that the stratigraphic successions of some units end with Early Miocene turbiditic deposits, which are characterised by a high content of mainly andesitic volcaniclastic detritus. These volcanogenic sediments, which are widespread both in the Betic Cordilleras (Algeciras Flysch [17]), in the Maghrebian Chain (Beni Ider Flysch and Mixed Successions in the Rif [18,19]; *Tufiti di Tusa* Fm. [16,20] in the Sicilian Maghrebids) and in the Southern Apennines (*Tufiti di Tusa* Fm. [21–23]), testify the presence, within or close to the basin, of a strongly active, calc-alkaline volcanic arc, penecontemporaneous as regards the sedimentation. Moreover, these sediments represent a basic marker for the reconstruction of the palaeogeographic and geodynamic evolution of the central-western Mediterranean area ([4,24] and references therein).

In this paper, the volcaniclastic debris-rich formations that characterise the Troina–Tusa Unit in the Sicilian sector of the Flysch Basin are examined in detail. The terrains of this unit are sandwiched between the overlying Monte Soro Unit and the underlying Nicosia and Panormide Units (Figs. 1 and 2). New field, biostratigraphic and petrographic data allow us a more detailed reconstruction of the structural and palaeogeographic evolution of the Flysch Basin in Sicily, immediately before the onset of the compressive deformation and the stacking of the basin-related terrains into the accretionary wedge of the developing Maghrebian Chain.

2. Previous studies

Volcaniclastic sediments, named as *Tufiti di Tusa*, have been first recognised by Ogniben [16,20] in the Sicilian sector of the Flysch Basin. They are comprised within one of the tectonic units of the Sicilide Complex (Troina Nappe), and they represent a part of an Eocene formation characterised by markedly heteropic facies (Tusa facies of the Polizzi Formation). According to this author, the Tusa facies is constituted by thick tuffitic beds, with a volcaniclastic content exceeding even 90%, which are interbedded with marls and limestones. The latter sometimes show reverse graded bedding, and they are characterised by a high amount of the larger foraminifera. The author points out the strong similarity of the volcaniclastic terrains of Sicily with the Taveyannaz Sandstones of the Helvetico-Delfinese Units of the Alps. Like the latter, they should represent the result of a synorogenic andesitic volcanism occurring between the Mesozoic ophiolitic magmatism and the Quaternary volcanic activity. Strangely, the author does not recognise the turbiditic origin of the tuffitic and carbonate deposits, and he interprets, as the source of the volcaniclastic materials, the lavas (limburgites *Auct.*), characterising some carbonate platform units of the Calabria–Lucania border area, arbitrarily considered Eocene in age and andesitic in composition.

Ten years later, Wezel and Guerrera [25] and Guerrera and Wezel [26] reached fully different conclusions. The volcaniclastic levels, which have an epiclastic origin, constitute the most frequent lithologies of an entirely turbiditic formation, deposited in a deep-sea environment and Late Oligocene–Middle Aquitanian in age, denominated *Tufiti di Tusa* Formation. The *Tufiti di Tusa* Fm. conformably overlies a formation characterised by varicoloured clayey facies (*Argille Varicolori* Fm.), and it constitutes the most recent stratigraphic unit of the succession of a tectonic sheet defined as Troina–Tusa Flysch Unit. The authors interpret the volcaniclastic deposits according to the plate tectonic model: the tuffitic formation has been fed by the erosion of a calc-alkaline volcanic arc, located in an internal position and related to a tectonically active margin in a compressive geodynamic environment.

Later, the *Tufiti di Tusa* Fm. has been mapped in different areas of central-northern Sicily, between the Madonie and the Nebrodi Mts. [27–31]. The formation has been recognised also in the Southern Apennines [21,22,32], but petrographic analyses have been carried out only in the Calabria-Lucania border area [23]. A consistent volcaniclastic content reaching 18–30% and, therefore, markedly lower than that characterising the *Tufiti di Tusa* Fm., has been pointed out by Puglisi [33] in the lower part of arenaceous turbiditic formations outcropping near Cerami and Troina and later by Cassola et al. [34] near Cefalù. These latter authors denominate these terrains as External Reitano Flysch, which has been interpreted as a Lower Oligocene formation deposited within small pull-apart basins, which characterised some external areas of the Sicilian sector of the Flysch Basin during the compressive deformation.

Guerrera et al. [4] and de Capoa et al. [35] discuss the volcaniclastic terrains in the evolutionary context of the Sicilian sector of the Flysch Domain: the formations containing volcaniclastic detritus, which are Burdigalian in age and heteropic to each other, constitute the uppermost part of the stratigraphic succession of the Troina–Tusa Unit, and they characterise the development of the foredeep sedimentation in the internal areas of the Flysch Domain.

3. Field data

The reexamination of a wide chain area across the Nebrodi and Madonie Mts. has allowed us to recognise three sectors within which the most recent terrains of the Troina–Tusa Unit are represented by different turbiditic formations, characterised by an abundant volcaniclastic content. These formations (*Arenarie di Poggio Maria*, *Tufiti di Tusa* and *Arenarie di Troina*) differ from each other as regards thickness, lithology and sedimentary facies. However, all these formations lie above a common substratum, which is made up of the *Argille Varicolori* Formation, are characterised by the same age and show a considerable content in volcanogenic fraction (Fig. 2), which justifies our interpretation considering them as heteropic formations.

3.1. Lascari–Cefalù sector

In the coastal area between the valleys of the Rio Imera, to the west, and the Torrente Carbone, to the east, some *klippen* of the Troina–Tusa Unit terrains (placed above the Numidian Flysch, which is related with the external carbonate units of the Panormide Complex) have been mapped for some time [28,34,35]. These *klippen* should be formed by terrains of the *Tufiti di Tusa* Fm. and arenaceous bodies considered as belonging to the Reitano Flysch Fm. As regards the relationships between the Reitano Flysch and the underlying *Tufiti di Tusa*, according to Lentini et al. [28] the Reitano Flysch conformably follows the *Tufiti di Tusa*, whereas Amodio Morelli et al. [36] consider the boundary between these two formations as an angular unconformity, and Cassola et al. [34] interpret the same as a tectonic boundary. Finally, de Capoa et al. [35], owing to the volcaniclastic content, ascribe the terrains formerly considered as a part of the Reitano Flysch to the *Tufiti di Tusa* Fm.

In all *klippen*, the revision of field data (Fig. 2, log 1) demonstrates that the terrains already considered as the *Tufiti di Tusa* Fm. are actually constituted by the typical lithologies characterising the upper part of the *Argille Varicolori* Fm., as redefined by Carbone et al. [30] and Lentini et al. [31]. Moreover, in the same *klippen*, the deposits formerly attributed to the Reitano Flysch [28,34,36] or to the *Tufiti di Tusa* Fm. [35] constitute a formation, made up only of arenaceous turbidites, that represents the stratigraphic evolution of the underlying *Argille Varicolori* Fm. Taking into account the lithologic features, the *Arenarie di Poggio Maria*, even if rich in volcaniclastic debris, cannot be considered a tuffitic formation, because the volcanogenic content does not exceed 30–35%. Therefore, these sediments belong to the field of the "impure volcaniclastic arenites" of Zuffa [37,38]; so they cannot be ascribed to the *Tufiti di Tusa* Fm., and they may be considered as a heteropic formation of this latter.

The *Argille Varicolori* Fm. crops out at the base of the eastern and southern slopes of Le Serre, and it is well observable along the Cefalù–Gibilmanna road. The same formation is also recognisable within the Rio Campella Valley, immediately to the north of Lascari and as far as the Imera River to the south and west of this village.

The formation (Fig. 2, log 1) is constituted by regularly alternated, sometimes laminated, varicoloured marly, clayey–marly and clayey layers containing beds of white, yellow and grey–greenish, sometimes silicified, allodapic limestones, which often show a turbiditic origin (i.e. the presence of the *Tb*, *Tc* and *Td* of the Bouma sequence). In the uppermost part of the succession, thin arenaceous layers at first appear, which are followed by abruptly occurring medium to very thick beds of grey–greenish sandstones. Intercalations of calcareous and marly layers also characterise some of the basal metres of the overlying sandstone succession, but upwards they disappear. This stratigraphic evolution can be observed in several places between Cefalù and Lascari, and it is particularly well exposed between kilometres 1 and 2 of the Cefalù–Gibilmanna road (Fig. 3a), in the Rio Campella Valley, immediately to the northeast of Lascari and to the east of Casale Giunchi.

The overlying arenaceous turbiditic formation extensively crops out between Cefalù and Lascari, where it constitutes the reliefs of Le Serre and Poggio Maria and for some kilometres along the coastal cliff extending from Capo Plaia to Capo Cefalù.

From a lithologic point of view, this formation, for which, in this paper, is informally proposed the denomination *Arenarie di Poggio Maria* Fm., is mainly constituted by medium- to coarse-grained, well cemented, sometimes microconglomeratic (clast dimension 3–5 mm), sandstones (Figs. 2, log 1; 3a–3c). The unit is generally characterised by grey–greenish (brownish if alterated) medium to thick and rarely thin layers and sometimes by very thick beds. From hand sample observation, it is possible to recognise euhedral feldspar clasts and little lava pebbles, together with quartz crystals showing magmatic corrosion and fragments of plutonic and metamorphic rocks. The turbiditic origin is testified by the presence of the Bouma sequence intervals, among which the *Ta* is only evident in the most coarse and microconglomeratic strata. Also, the *Tb*, *Tc* and *Td* intervals are only sometimes observable. The pelitic interval is usually missing, and it has rarely been found in the lower and in the upper parts of the formation, whereas clay chips have frequently been recognised. Also, sedimentary structures at the base of the strata are rare, while load- and water loss-related features are common. The thickest beds seem to be the result of grain flow deposition. The maximum outcropping thickness is about 250 m.

3.2. *Castel di Tusa–Mistretta–San Teodoro sector*

This sector represents the area where the *Tufiti di Tusa* Fm., as described by Ogniben [16,20], Wezel and Guerrera [25] and Guerrera and Wezel [26], crops out. The outcrops are always of small dimensions, and the widest ones are located near the archaeological site of Halaesa (some kilometres from Castel di Tusa) and near Mistretta and San Teodoro. The stratigraphic successions are similar across the three sites even if, near Halaesa, because of high thicknesses and well exposed intervals, it is possible to better recognise the different lithofacies characterising the formation.

In the Halaesa area, the Troina–Tusa Unit tectonically lies above the Numidian Flysch of the Panormide Complex, and it is represented both by the *Argille Varicolori* Fm. and by the *Tufiti di Tusa* Fm. The terrains of the Troina–Tusa Unit are usually arranged in imbricated tectonic sheets, varying in thickness from some tens of metres to several hundreds of metres (over 600 m in the uppermost sheet). Frequent redoublings and overturnings of more or less thick stratigraphic intervals occur. The Reitano Flysch deposits lie unconformably above these tectonic sheets.

The *Argille Varicolori* Fm. is constituted by varicoloured clays with interbedded fine-grained calcareous turbidite layers. The formation passes to the overlying tuffitic sediments through a sharp contact, and its uppermost part is affected by slumping.

On the basis of the lithologic and sedimentologic field data, in the *Tufiti di Tusa* Fm., different turbiditic lithofacies are recognisable (Fig. 3d–f). In the Halaesa area (Fig. 2, log 2), the formation is made up of alternating silty–marly, arenaceous, rarely conglomeratic and carbonate turbidites, containing a few thin layers of hemipelagic clays that are recognisable for their typical greyish olive colour. The silty–marly turbidites constitute the most abundant lithofacies, and they are formed by laminated siltites, usually lacking in the basal interval with graded bedding, and which grade upwards into greyish silty marls. Siltites are characterised by a high volcaniclastic content, and they are characterised by the presence of fossil traces such as *Paleodictyon* and *Granularia*. Within some intervals, the marls become lighter and contain a great variety and amount of ichnofauna, among which the Helminthoidea type prevails.

Arenaceous, typically volcaniclastic, turbidites are more frequent in the upper part of the succession. They range from greenish to bluish in colour, and the thickness of the layers is varying, from some tens of centimetres to several metres (up to 14), but 2–3 m thick beds prevail. These volcaniclastic arenites, which are generally fractured, are characterised by graded bedding and fine to medium grain size (up to 2.5 mm), are from well to moderately sorted and often contain marly, calcareous and siltitic intraclasts, which are concentrated in the upper part of the layers. Palaeocurrent marks, indicating a varying direction and sense of provenance, frequently occur.

The calcareous turbidites are less common in the lowermost part of the formation. They are represented by whitish calcilutite and calcarenite layers showing graded bedding and varying in thickness from 0.4 to 2 m. Graded, parallel and convolute bedding, and flute and groove casts testify the turbiditic origin of the calcilutites; such an origin is more evident for the calcarenitic lithofacies, which contain benthic larger foraminifera and algal fragments and other resedimented neritic fossils; moreover, hemipelagic clays, centimetric in thickness, are still less frequent.

The structural framework of the *Tufiti di Tusa* Fm. near Mistretta is more complex (Figs. 1; 2, log 3). In fact, in this area between the *Tufiti di Tusa* Fm. and the base of the transgressive Reitano Flysch, a lenticular body, nearly 100 m thick, of highly deformed *Argille Varicolori* is interbedded. This body comprises also different lithic blocks and beds (calcirudites, calcilutites, calcarenites with graded

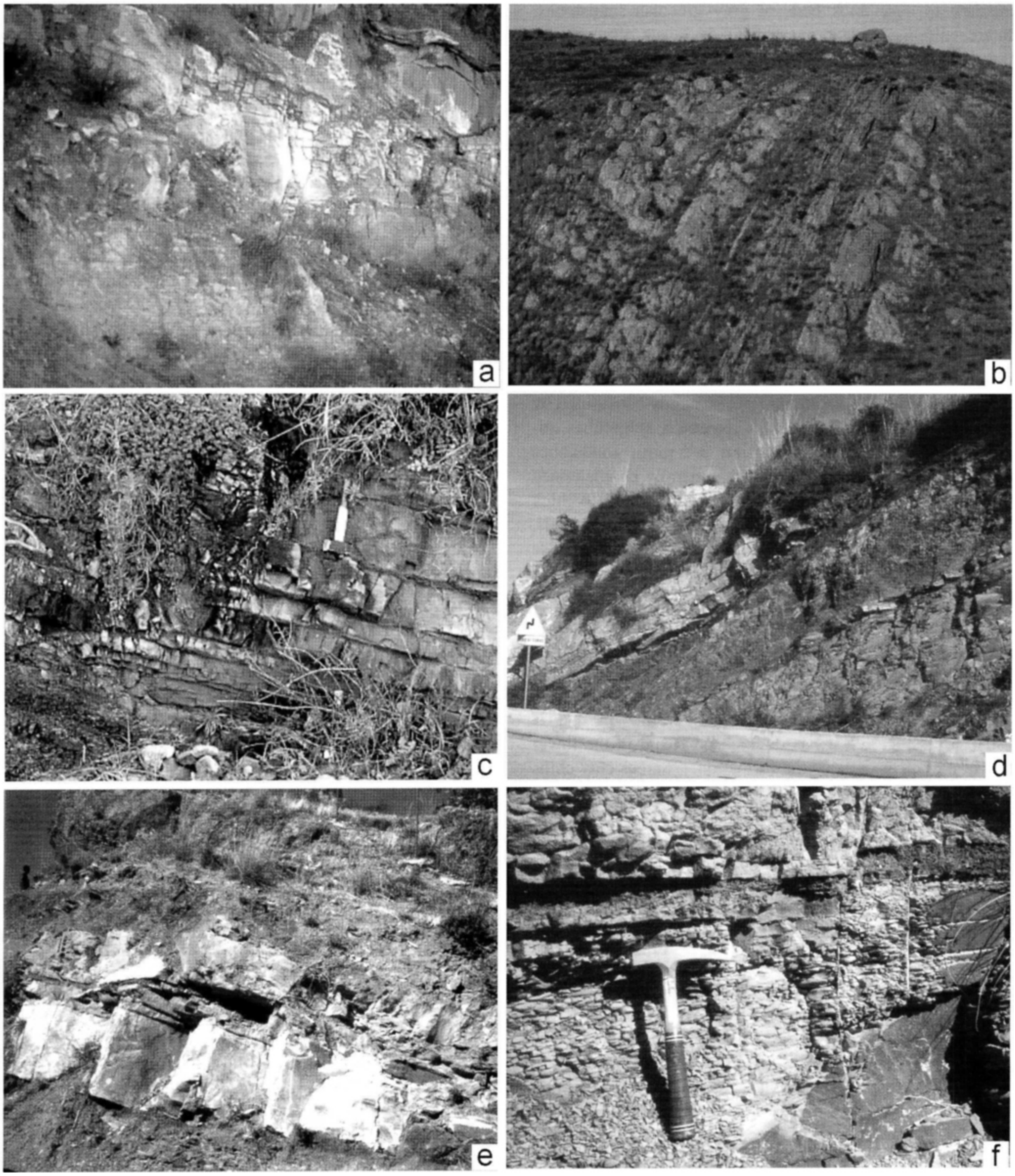

Fig. 3. Features of the *Arenarie di Poggio Maria* and *Tufiti di Tusa* Fms. (a) Transition between the *Argille Varicolori* Fm. and the *Arenarie di Poggio Maria* Fm. along the Cefalù–Gibilmanna road. Typical volcaniclastic turbidites of the *Arenarie di Poggio Maria* Fm.: (b) Poggio Maria area (upper levels); (c) Capo Cefalù area. Typical volcaniclastic turbidites of the *Tufiti di Tusa* Fm.: (d) San Teodoro section; (e, f) Halaesa section.

bedding containing spherical quartz grains, arenites), which are related with the carbonate covers of the Peloritanian units and the Cretaceous levels of the Monte Soro Flysch Unit. This deformed succession, which can be related to the Monte Pomiere Fm. [39], represents a typical olistostrome, mechanically lying above the *Tufiti di Tusa* Fm. It may be interpreted as the stratigraphic base, in the Mistretta area, of the Reitano Flysch Fm. (Figs. 1; 2, log 3).

In the San Teodoro area, the *Tufiti di Tusa* Fm., which conformably follows the *Argille Varicolori* Fm., crops out to a thickness of about 250 m (Fig. 2, log 4). Even if the thickness is reduced here, the whole lithologic succession and structural features are quite similar to those described for the Halaesa sector. Occasional slumps are also recognisable; their thickness does not exceed 6 m and they comprise marly and arenitic lithofacies.

All the described features lead to the consideration of the sedimentation of the *Tufiti di Tusa* Fm. as related with gravitational deep processes, on a rather flat sea bottom, probably in an abyssal plain, involving a very abundant amount of volcaniclastic detritus.

3.3. Troina–Cerami sector

In this area, abundant volcaniclastic debris has been recognised by Puglisi [33,40] in the basal part of the External Reitano Flysch. This stratigraphic unit has been redefined as *Arenarie di Troina* Fm., and it has been considered as heteropic of the *Tufiti di Tusa* Fm. by de Capoa et al. [35].

The *Arenarie di Troina* Fm. characterises the reliefs of Troina and Cerami villages, emerging with their steep slopes from the gentle landscape related with the underlying *Argille Varicolori* Fm. (Figs. 1 and 4a). The lower part of the *Arenarie di Troina* Fm. crops out also in the Ancipa Lake area and in the Serro Scarvi relief, some kilometres south-east of Troina, where a minor thrust leads the *Argille Varicolori* Fm. to override their overlying arenaceous sediments.

The *Arenarie di Troina* Fm. is characterised at the base by a sandy–conglomeratic bed some metres thick that abruptly conformably overlies the calcareous–marly deposits, containing some intercalations of sandstone layers, characterising the uppermost part of the *Argille Varicolori* Fm. This latter formation presents the same features already pointed out for the previously described sectors, being constituted by sometimes laminated grey marls and clays, interbedded with marly limestones and sometimes silicified

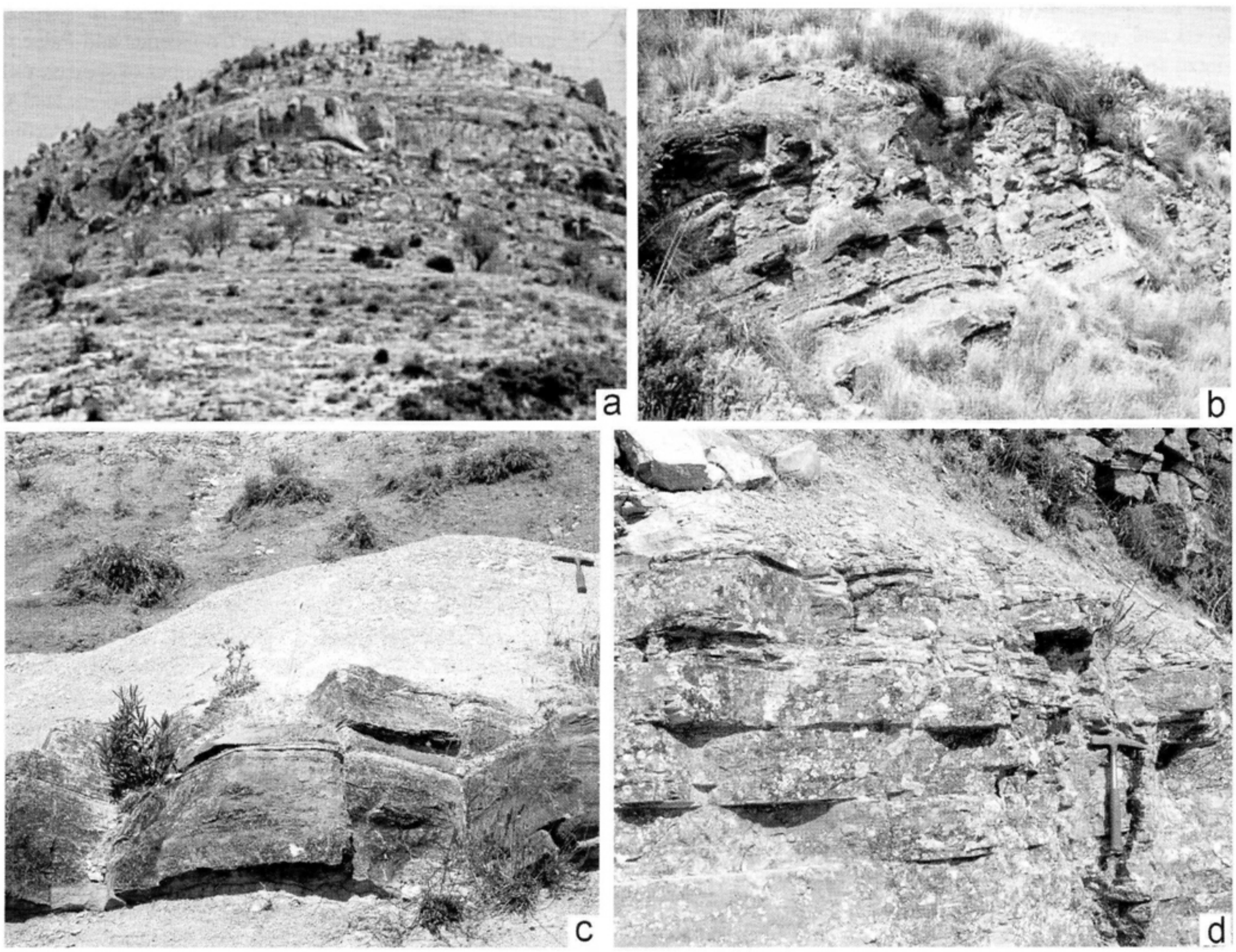

Fig. 4. Features of the *Arenarie di Troina* Formation in the Cerami area: (a) the uppermost strata of the *Argille Varicolori* Fm. and the basal levels of the *Arenarie di Troina* Fm. near Mt. Grottelle; (b) the lower member in the south Cerami section; (c) the intermediate member in the south Cerami section; (d) the upper member in the south Cerami section.

whitish and greenish calcilutites. In all the examined sections, the appearance, in the uppermost part of the formation, of arenaceous beds, about decimetric in thickness, indicates the beginning of the siliciclastic sedimentation, and it confirms a transitional evolution from the *Argille Varicolori* Fm. to the *Arenarie di Troina* Fm.

The stratigraphic succession of the *Arenarie di Troina* Fm., which has been described in detail by Loiacono and Puglisi [41] and Cassola et al. [42], is characterised by three very different lithologic intervals (Fig. 2, logs 5 and 6). The formation begins with an interval, reaching up to 100 m in thickness, constituted by sometimes channelled thick conglomeratic and arenaceous beds. They are grey in colour, or brownish for alteration, and sometimes they are arranged in amalgamated beds with no internal organisation, within which less thick and fine-grained sandy layers are interbedded. These deposits evolve upwards into thin to medium thick well layered sandstones, which are sometimes characterised by all the intervals of the Bouma sequence (Figs. 2, logs 5 and 6; 4b).

This interval is followed by medium- and fine-grained, thin to medium thick sandy and sandy–pelitic turbidite layers and, upwards, by clays and siltites, containing occasional arenaceous and calcareous beds and thin hemipelagic levels (Figs. 2, logs 5 and 6; 4c). The thickness of this interval ranges between 100 and about 330 m. At the top, the succession again becomes coarser, and the pelitic–siltitic alternation is replaced by an interval up to 110 m thick, constituted by well layered thick sandstones, containing thin pelitic intercalations (Figs. 2, logs 5 and 6; 4d).

The volcaniclastic fraction is easily recognisable in the hand samples only in the conglomeratic and arenaceous levels of the basal interval, where it reaches an amount of about 30% [33,41]. Upwards, the volcaniclastic fraction rapidly decreases, and in the uppermost levels, it is limited to 1–3%.

4. Biostratigraphy

The biostratigraphic characteristics of the uppermost part of the *Argille Varicolori* Fm. and the overlying volcaniclastic formations have been pointed out by de Capoa et al. [35]. The study of foraminifera and coccoliths allows the authors to recognise an Early Miocene age for the uppermost part of the *Argille Varicolori* Fm. and the overlying siliciclastic formations. Among the latter, it is possible to obtain more detailed data for the *Tufiti di Tusa* and *Arenarie di Troina* Fms.; in fact, the first formation is characterised by taxa of Burdigalian age already from the lowermost levels, and the second one evidences a Late Burdigalian age for the uppermost levels.

In this paper, we carried out a new and more detailed biostratigraphic study also through the utilisation of dinocysts, which have been recognised for the first time within the Maghrebian Flysch Basin-related terrains. The coccolith assemblages have been interpreted according to the Neogene nanofossil biostratigraphic zonation proposed by Young [43]. The results basically confirmed the datings of de Capoa et al. [35].

For their turbiditic origin, the siliciclastic formations have not been easy to date, in particular as regards the *Arenarie di Poggio Maria* Fm., which is lacking in pelitic levels. On the contrary, the *Tufiti di Tusa* Fm. and the immediately underlying *Argille Varicolori* Fm. have been more easily dated because of the abundance of pelitic levels.

The uppermost 30 m of the *Argille Varicolori* Fm. have been sampled in the Lascari–Cefalù sector in the Rio Campella valley and along the Cefalù–Gibilmanna road. The same levels have also been sampled in Halaesa, Mistretta and San Teodoro sections, and moreover in the East Troina and South Cerami sections; these latter are located along state road 120 and on the southern side of Mt. Grottelle, respectively (Fig. 2).

The coccoliths recognised within the *Argille Varicolori* Fm. are shown in Table 1. The stratigraphically significant taxa are rather limited (*Discoaster druggii*, *Umbilicosphaera rotula*, *Helicosphaera ampliaperta*, *H. carteri*, *H. gertae*), while clearly reworked Cretaceous and Palaeogenic taxa are markedly prevalent in number of species and abundance of specimens. All the abovesaid markers testify an age not older than Early Miocene (Zone NN2 of Martini [44] = Zone CN1c of Okada and Bukry [45]). In particular, *D. druggii* starts in Zone NN2 and *H. ampliaperta* in the upper part of the same Zone NN2, which, according to Young [43], marks the base of the Burdigalian. Consequently, the upper layers of the *Argille Varicolori* Fm. are certainly Early Miocene in age and, at least in some areas, reach the Burdigalian. This age is in agreement with that of the *Tufiti di Tusa* Fm., whose lower layers show taxa starting from Zone NN3 (see below).

As regards the dinocysts (Table 2), the most important datum is represented by the presence of *Nemathosphaeropsis labirinthea*, whose FO (first occurrence) is indicated at the base of Zone DM1 of Biffi and Manum [46], which corresponds with the upper part of Zone NN1 of Martini [44] = CN1b of Okada and Bukry [45]. Therefore, the age is not older than Aquitanian, and most of the recognised species (*Hystrichokolpoma rigaudiae*, *Paleocystodinium golzowense*, *Selenopemphix nephroides*, *Spiniferites ramosus*, *Systemathophora placacantha*) are compatible with this age, while other taxa (*Deflandrea phosphoritica*, *Homotriblium oceanicum*, *Hystrichokolpoma cinctum*, *Pentadinium goniferum*), which have a distribution limited to the Eocene–Oligocene time span, should be considered as reworked.

The samples of the pelites interbedded within the arenaceous volcaniclastic detritus-rich formations have been collected in the eastern side of Poggio Maria, starting from Rio Campella, along the Cefalù–Gibilmanna road and along the coast east of Capo Playa (*Arenarie di Poggio Maria* Fm.), in the well known Halaesa and San Teodoro sections (*Tufiti di Tusa* Fm.) and, as regards the *Arenarie di Troina*

Table 1
Argille Varicolori Formation: coccoliths

Braarudosphaera bigelowi
Bramletteius serraculoides
Coccolithus miopelagicus
Coccolithus miopelagicus >20 μm
Coccolithus pelagicus
Coronocyclus nitescens
Cyclicargolithus abisectus
Cyclicargolithus floridanus
Discoaster adamanteus
Discoaster calculosus
Discoaster deflandrei
Discoaster cf. *deflandrei*
Discoaster druggii
Discoaster aff. *Formosus*
Discoaster spp.
Ericsonia cava
Ericsonia obruta
Helicosphaera ampliaperta
Helicosphaera carteri
Helicosphaera* cf. *carteri
Helicosphaera euphratis
Helicosphaera cf. *euphratis*
Helicosphaera gertae
Helicosphaera cf. *recta*
Helicosphaera truempyi
Pedinocyclus larvalis
Pontosphaera ocellata
Pontosphaera spp.
Pyrocyclus hermosus
Reticulofenestra daviesi
Reticulofenestra gartneri
Reticulofenestra perplexa
Reticulofenestra sp.
Rhabdosphaera pinguis
Sphenolithus conicus
Sphenolithus cf. *conicus*
Sphenolithus moriformis
Sphenolithus sp. A
Sphenolithus spp.
Thoracophaera spp.
Triquetrorhabdulus carinatus
Triquetrorhabdulus cf. *carinatus*
Umbilicosphaera rotula

Bold type = marker.

Table 2
Argille Varicolori Formation: dinocysts

Deflandrea phosphoritica[a]
Homotriblium oceanicum[a]
Hystrichokolpoma cinctum[a]
Hystrichokolpoma rigaudiae
Nemathosphaeropsis labirinthea
Paleocystodinium golzowense
Pentadinium goniferum[a]
Selenopemphix nephroides
Spiniferites ramosus
Systemathophora placacantha

Bold type = marker.
[a] Reworked taxa.

Fm., along state road 575 at Troina and near Cerami, between Mt. Grottelle, Timpone Calumeli and the water reservoir.

Table 3
Arenarie di Poggio Maria Formation: coccoliths

Coccolithus miopelagicus
Coccolithus pelagicus
Cyclicargolithus abisectus
Cyclicargolithus floridanus
Discoaster spp.
Ericsonia cava
Ericsonia fenestrata
Ericsonia Formosa
Helicosphaera carteri
Helicosphaera euphratis
Reticulofenestra perplexa
Sphenolithus moriformis
Sphenolithus sp. A
Triquetrorhabdulus carinatus
Triquetrorhabdulus cf. *carinatus*

Bold type = marker.

The coccoliths recognised within the *Arenarie di Poggio Maria*, *Tufiti di Tusa* and *Arenarie di Troina* Fms. are shown in Tables 3, 4 and 7, respectively. In Tables 5 and 6, which are related with the *Tufiti di Tusa* Fm., foraminifera and dinocysts are also indicated. As already observed for the *Argille Varicolori* Fm., reworked taxa prevail both in species and specimen number.

The *Arenarie di Poggio Maria* Fm. furnished very poor nanofloras, and the most significative taxon (*Helicosphaera carteri*) allows us to define an age not older than Aquitanian (Zone NN2 of Martini [44] = Zone CN1c of Okada and Bukry [45]), but the age of the formation is certainly younger, considering that the underlying *Argille Varicolori* Fm. reaches the upper part of Zone NN2.

Among the coccoliths from the *Tufiti di Tusa* Fm. (Table 4), the markers are represented by *Discoaster druggii*, *Umbilicosphaera rotula*, *Helicosphaera carteri*, *H. gertae*, *Triquetrorhabdulus milowii* and *Sphenolithus belemnos*. In particular, the FO of this latter taxon is indicated in Zone NN3 of Martini [44] = Zone CN2 of Okada and Bukry [45]; therefore, the age of the *Tufiti di Tusa* Fm. is not older than Middle Burdigalian. This age is confirmed by the recognised foraminifera (*Globigerina woodi*, *Globigerinita naparimaensis* and *Globigerinoides* gr. *trilobus*), which start as from the Burdigalian (Zones N5 and N6 of Blow [47]; Table 5). As regards the dinocysts (Table 6), also in the *Tufiti di Tusa* Fm., the most representative taxon is *Nemathosphaeropsis labirinthea*, whose first occurrence is reported starting from the Aquitanian, Zone DM1 of Biffi and Manum [46] = upper part of the Zone NN1 of Martini [44] = Zone CN1b of Okada and Bukry [45].

In the lower part of the *Arenarie di Troina* Fm., only an age not older than Early Miocene is definable, owing to the presence of *Helicosphaera carteri*, *H. gertae* and *Umbilicosphaera rotula*. Instead, the middle–upper part of the formation may be considered Late Burdigalian in age, because of the occurrence of *Calcidiscus leptoporus*, *C. macintyrei* and *Discoaster variabilis*, whose FO is

Table 4
Tufiti di Tusa Formation: coccoliths

Braarudosphaera bigelowi
Coccolithus miopelagicus
Coccolithus miopelagicus >20 μm
Coccolithus pelagicus
Coronocyclus nitescens
Cyclicargolithus abisectus
Cyclicargolithus floridanus
Discoaster adamanteus
Discoaster aff. *adamanteus*
Discoaster cf. *adamanteus*
Discoaster calculosus
Discoaster deflandrei
Discoaster cf. *deflandrei*
Discoaster druggii
Discoaster spp.
Ericsonia cava
Ericsonia Formosa
Ericsonia obruta
Helicosphaera carteri
Helicosphaera euphratis
Helicosphaera truempyi
Helicosphaera sp.
Pontosphaera discopora
Pyrocyclus hermosus
Reticulofenestra gartneri
Reticulofenestra perplexa
Sphenolithus belemnos
Sphenolithus conicus
Sphenolithus moriformis
Sphenolithus sp. A
Thoracophaera spp.
Triquetrorhabdulus carinatus
Triquetrorhabdulus cf. *carinatus*
Triquetrorhabdulus milowii
Triquetrorhabdulus* cf. *milowii
Umbilicosphaera rotula

Bold type = marker.

Table 5
Tufiti di Tusa Formation: foraminifera

Globigerina woodi
Globigerina connecta
Globigerinoides* gr. *trilobus
Globigerinita naparimaensis
Globigerinita baroemoenensis
Globoquadrina dehiscens
Globoquadrina cf. *dehiscens*
Globorotaloides suteri
Catapsydrax unicavus
Catapsydrax dissimilis

Bold type = marker.

Table 6
Tufiti di Tusa Formation: dinocysts

Deflandrea phosphoritica[a]
Hystrichokolpoma rigaudiae
Nemathosphaeropsis labirinthea
Paleocystodinium golzowense
Selenopemphix nephroides
Spiniferites mirabilis
Spiniferites ramosus
Wetzeliella gochti[a]

Bold type = marker.
[a] Reworked taxa.

Table 7
Arenarie di Troina Formation: coccoliths

Braarudosphaera bigelowi
Calcidiscus leptoporus
Calcidiscus macintyrei
Coccolithus miopelagicus
Coccolithus miopelagicus >20 μm
Coccolithus pelagicus
Coronocyclus nitescens
Cyclicargolithus abisectus
Cyclicargolithus floridanus
Discoaster aff. *prepentaradiatus*
Discoaster variabilis
Discoaster spp.
Ericsonia cava
Helicosphaera carteri
Helicosphaera euphratis
Helicosphaera gertae
Pontosphaera sp.
Pyrocyclus hermosus
Reticulofenestra gartneri
Reticulofenestra perplexa
Sphenolithus moriformis
Thoracophaera sp.
Triquetrorhabdulus carinatus
Umbilicosphaera rotula

Bold type = marker.

indicated within Zone NN4 of Martini [44] = Zone CN3 of Okada and Bukry [45].

In conclusion, coccoliths, foraminifera and dinocysts testify that the uppermost part of the *Argille Varicolori* Fm. is constituted by Lower Miocene layers, which, at least in some sections, may be Burdigalian in age, as indicated by the occurrence of *H. ampliaperta*, starting from the upper part of Zone NN2, and by the Middle Burdigalian age (Zone NN3) of the lower part of the overlying *Tufiti di Tusa* Fm. The lower part of other volcaniclastic detritus-rich formations (*Arenarie di Poggio Maria* and *Arenarie di Troina*) is Early Miocene in age, but taxa starting from Burdigalian, which have been recognised in the *Tufiti di Tusa* Fm., have not been found in these formations. However, we also consider these formations Burdigalian in age, taking into account the age of the underlying *Argille Varicolori* Fm. and the difficulty to admit a diachronous onset for the volcaniclastic sedimentation. As regards the age of the uppermost part of the volcaniclastic formations, taxa whose first occurrence is most recent have been recognised in the upper levels of the *Arenarie di Troina* Fm.; they indicate an age not older than Late Burdigalian (Zone NN4 of Martini [44] = Zone CN3 of Okada and Bukry [45]). However, these Upper Burdigalian levels are lacking in volcaniclastic detritus. Taking also into account the lack of volcaniclastic debris in the overlying Reitano Flysch sedimentary cycle, we may conclude that the volcaniclastic sedimentation affected the Sicilian sector of the Maghrebian Flysch Basin starting from Burdigalian and probably ended during this stage.

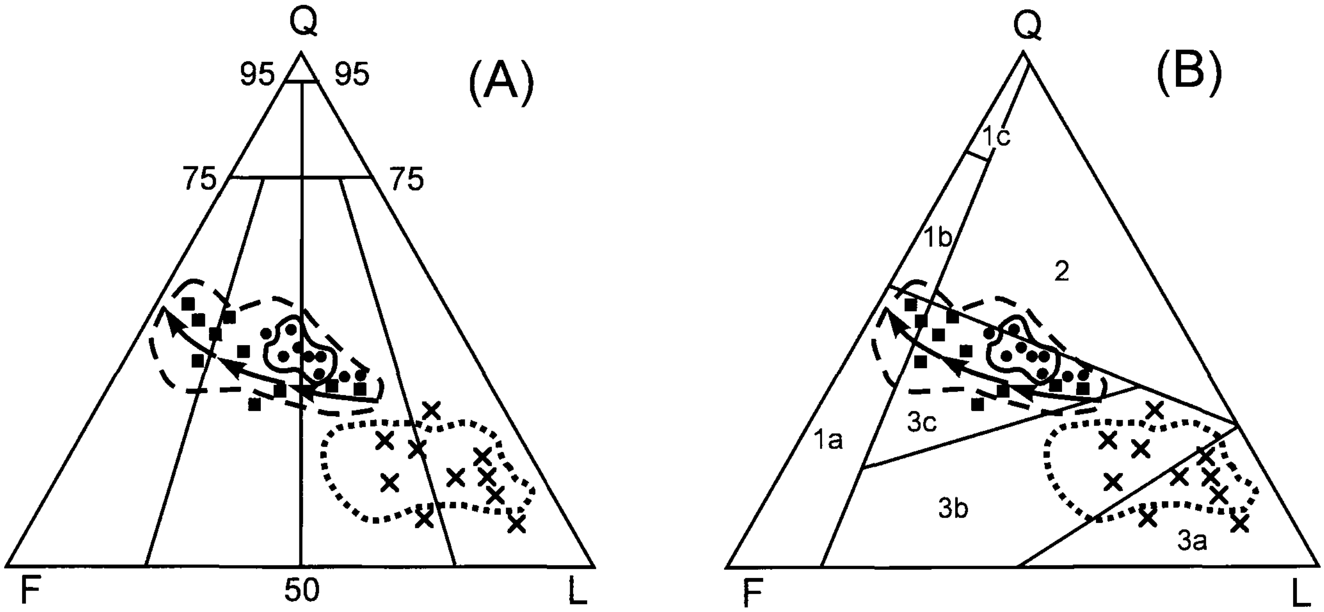

Fig. 5. QFL (quartz–feldspars–lithic fragments) diagram for the studied volcaniclastic formations (a) and QFL diagram showing relations between sandstone composition and geodynamic setting (b) according to Dickinson and Suczek [48] and Dickinson [49,50]: 1, continental block (1a, basement uplift; 1b, transitional; 1c, craton interior); 2, recycled orogen; 3, magmatic arc (3a, undissected arc; 3b, transitional arc; 3c, dissected arc). —— Compositional field of the *Arenarie di Poggio Maria* Fm. according to Cassola et al. [34]; • new data from this study; ··· compositional field of the *Tufiti di Tusa* Fm. in the Southern Apennines according to Critelli et al. [23]; × new data from this study; – – – compositional field of the *Arenarie di Troina* Fm. according to Cassola et al. [34]; ■ new data from this study. Arrow: compositional trend of the *Arenarie di Troina* Fm. according to Cassola et al. [34].

5. Petrography

Petrographic data from six samples of the *Arenarie di Poggio Maria* Fm. have already been shown by Cassola et al. [34]. These samples straddle the boundary between feldspathic litharenites and lithic arkoses (Fig. 5a), with volcanic lithic fragments comprised between 16.8 and 21.3 vol.% and plagioclases of volcanic origin between 14.4 and 19.7 vol.%; quartz grains and subordinate feldspars and lithic fragments deriving from acid plutonites and middle- to high-grade metamorphic rocks are also present.

New petrographic analyses from 10 samples (Fig. 5a) generally agree with the data of Cassola et al. [34]. The *Arenarie di Poggio Maria* Fm. is characterised by prevailing quartz–feldspathic fragments deriving from plutonites and by middle- to high-grade metamorphic rocks, together with an abundant volcaniclastic fraction, made up of volcanic glass, andesitic to dacitic lava fragments and crystals of volcanic origin (andesitic lava-derived minerals) (Fig. 6a, b). It is noteworthy that the petrographic composition of the *Arenarie di Poggio Maria* Fm. sandstones does not present significant variations across the whole stratigraphic succession.

On the basis of the diagrams of Dickinson and Suczek [48] and Dickinson [49,50], the debris constituting the *Arenarie di Poggio Maria* Fm. can be related with dissected arcs and recycled orogens (Fig. 5b).

Petrographic studies on the *Tufiti di Tusa* Fm. sandstones have never been carried out up to now in Sicily, and the only available data for comparison are those reported by Critelli et al. [23] for the *Tufiti di Tusa* Fm. outcropping in the Southern Apennines, in the Calabria–Lucania border area (Fig. 5a). The petrographic study of 12 samples from the Halaesa and San Teodoro sections points out a main volcano–arenitic composition associated with a subordinate litho-feldspathic composition (Fig. 5a). The study confirms the epiclastic nature of the volcanic clasts, which constitute up to 80–85% of detritic grains and are represented by porphyritic rock fragments, glass shards, and mono- and polymineralic grains (Fig. 6c, d). The rock fragments, which have andesitic and subordinately dacitic composition, show porphyritic to sub-aphyric textures, characterised by plagioclases and mafic minerals in a micro- and cryptocrystalline groundmass. Among the volcanic minerals, it is possible to recognise euhedral zoned plagioclases with andesitic composition ($An_{42–43}$), green hornblende, augitic clinopyroxene and small amounts of biotite, magnetite, titano-magnetite and resorbed quartz (Fig. 6c, d). Together with the volcano-derived fraction, detrital grains from metamorphic and plutonic rocks can be also observed. They are represented by quartz–feldspathic grains derived from high-grade metamorphic rocks (micaschists, amphibole and garnet gneisses, augen gneisses) and acid plutonic ones (granitoids), as well as rare clasts from low-grade metamorphic rocks (phyllites, metarenites and quartzites). Many heavy minerals (garnet, zircon, apatite, anathase, rutile, brookite, magnetite, titanite, clinozoisite, tourmaline, epidote) are recognisable. Sedimentary rock fragments are rare, and they are represented by limestones, shales and sandstones. Among the bioclasts, large foramini-

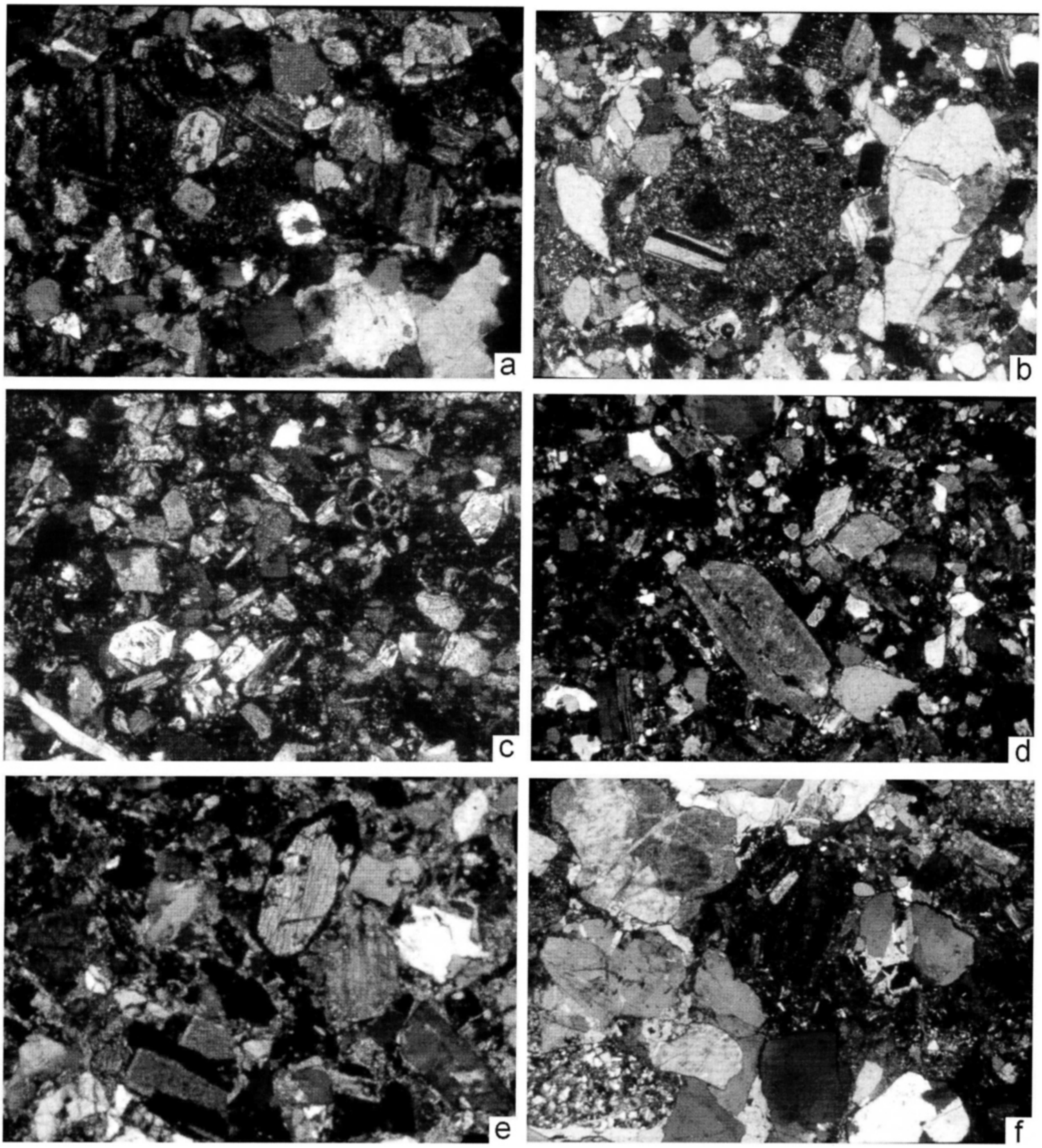

Fig. 6. Photomicrographs (cross-polarised light; 15×) of main framework grains and interstitial components from the volcaniclastic formations of the Troina–Tusa Unit: (a, b) *Arenarie di Poggio Maria* Fm.; (c, d) *Tufiti di Tusa* Fm.; (e, f) *Arenarie di Troina* Fm. An abundant volcaniclastic fraction (plagioclases, andesitic rock fragments, pyroxenes, volcanic glass, etc.) is recognisable in all photos.

fer, mollusc and algal remnants are present. The interstitial component is mainly represented by a non-carbonate pseudo-matrix [51] made up of clay minerals resulting from diagenetic alteration of volcanic silicates and glass.

The petrographic features of the *Tufiti di Tusa* Fm. are generally homogeneous along the whole stratigraphic succession, and they are very similar to those recognised by Critelli et al. [23] in the *Tufiti di Tusa* Fm. of the Southern

Apennines. However, a major lithologic variability characterises the *Tufiti di Tusa* Fm. of the Southern Apennines, where Critelli et al. [23] pointed out four different petrofacies, probably related to a more complex physiography of the basin and its palaeotectonic evolution.

According to the diagrams of Dickinson and Suczek [48] and Dickinson [49,50], the composition of the *Tufiti di Tusa* Fm. plots in the undissected and transitional arc fields (Fig. 5b).

The petrographic features of the *Arenarie di Troina* Fm. have been well described by Puglisi [33] and Loiacono and Puglisi [41]. The most interesting datum is that the petrographic composition of the sandstones, in this latter formation, presents highly different characteristics for each of its three members. In the succession, in fact, a markedly sharp trend can be identified from feldspathic litharenites, which are rich in volcaniclastic fraction, at the bottom, to arkose almost lacking in volcanic grains, in the upper portion (Fig. 5a). Within the basal conglomeratic–arenaceous member, the volcaniclastic fraction constitutes between 22% and 30% of the rock, and andesitic fragments exceed 50% of the lithic ones. In the intermediate member, the volcaniclastic fraction is about 9–18%, and the andesites constitute between 28% and 40% of the rock fragments. Finally, in the upper member, the volcaniclastic fraction lowers to values comprised between 1% and 3%, and the andesites represent less than 10% of the rock fragments. We analysed 10 thin sections of samples of the *Arenarie di Troina* Fm. (Fig. 6e, f), and our results (Fig. 5a) are similar to those of Puglisi [33] and Loiacono and Puglisi [41].

According to the diagrams of Dickinson and Suczek [48] and Dickinson [49,50], the *Arenarie di Troina* Fm. shows a trend from dissected arcs to recycled orogens to basement uplift fields (Fig. 5b).

All these data can be explained by the presence of a volcanic arc located above an orogenic belt made up of plutonic and metamorphic rocks. This volcanic arc was quickly eroded and completely dismantled; at this moment, the volcaniclastic supply ended, and the basin was filled only by plutonic and metamorphic clasts. This evolution is well recorded in the *Arenarie di Troina* basin, located in a more external position; its sandstones show a composition which agree well with the general trend of provenances from plutonic–volcanic arcs in the circum-Pacific trench–arc systems [49,50,53].

6. Results and discussion

In the Sicilian sector of the Maghrebian Flysch Basin, some turbiditic formations (*Arenarie di Poggio Maria*, *Tufiti di Tusa* and *Arenarie di Troina*), which characterise the uppermost part of the stratigraphic succession of the Troina–Tusa Unit and contain more or less abundant volcaniclastic debris, have been dated as Early Miocene in age.

These formations testify the evolution of the Maghrebian Flysch Basin to a foredeep, which is characterised by a high volcaniclastic supply, which is probably restricted to the Burdigalian. The foredeep was located close to an active calc-alkaline volcanic arc, which provided abundant volcaniclastic material. The proximity of the arc to the sedimentary basin is demonstrated by: (a) high amount of volcaniclastic debris both vertically (over 600 m in thickness, with very thick turbiditic—up to 14 m—beds) and laterally; (b) widespread presence of fresh volcanogenic material indicating a high rate of erosion and burial; (c) sandy grain size of sediments. However, we cannot exclude, for a part of the finest volcanogenic sediments, an origin from areas located far from the basin.

Besides, the volcaniclastic debris have mainly an epiclastic and not a pyroclastic origin, and it is linked to a rapid sub-aerial erosion and reworking of lavas and pyroclastics.

In conclusion, the volcanic sandstones indicate a sedimentation which is penecontemporaneous to the development of the calc-alkaline arc. This is probably located above a complex substratum, made up of pre-Alpine metamorphic and plutonic complexes covered by Meso–Cenozoic carbonates, as the abundant siliciclastic and sedimentary debris mixed together with the volcanogenic one indicate. In Sicily, the abovesaid rocks may be observed in the Peloritanian units.

The arenaceous formations, even if they are all turbiditic ones, are characterised by successions which are different in lithology, facies and thickness; however, they show the following common features: the same substratum, which is represented by the lithotypes of the *Argille Varicolori* Fm., a Burdigalian age, an abundant volcaniclastic content, more or less abundant non-volcaniclastic debris, represented by clasts from medium- to high-grade metamorphites and acidic plutonites and, except for the *Arenarie di Troina* Fm., the lack of any vertical evolution of the petrographic characteristics and turbidite facies. It is to be noted that the petrographic characters of the studied formations, which are rich in volcaniclastic debris, are markedly different with respect to those of other coeval turbiditic formations outcropping across the region (such as the Stilo–Capo d'Orlando Formation), which lack in debris having a volcanic origin and show a metamorphic debris mainly deriving from low-grade metamorphics.

In agreement with Dickinson et al. [52] and Dickinson [49,50], the sandstone composition points out an evolution, from undissected to dissected volcanic arcs, for the source area of the clastic supply. In the *Arenarie di Troina* Fm., however, it is possible to observe the successive passage from a magmatic arc to a recycled orogen and finally to a continental block (basement uplift). This evolution is admissible considering, as the source area for the clastic material, some crystalline basements that have an active volcanic arc above, later replaced by a rapidly eroded remnant arc. Later, this arc becomes completely demolished, as is testified by the lack of volcaniclastic material within the unconformable deposits of the overlying sedimentary cycle. This cycle, represented by the Reitano Flysch Fm., lies unconformably above all the stacked units of the Flysch Basin. A similar evolution has been pointed out for the Southern Apennines by Critelli et al. [53] and Critelli [54].

The differences in amounts of volcaniclastic material, thickness and facies observed for the studied formations may be explained only supposing an extremely complex palaeogeography. One has to admit the presence of depositional basins with a complex physiographic setting and source areas characterised by a varying amount, in space and time, of available volcanic materials. Dams or channel systems are responsible for the amount of sediments in different areas. This allows us to explain the abundance of epiclastic volcanic material within the *Tufiti di Tusa* Fm., which is characterised by a high sedimentation rate indicating depocentral areas, and the almost complete lack of epiclastic volcanic material in the basin of the coeval Stilo–Capo d'Orlando Fm. In this latter formation, located above the already stacked Peloritanian nappes in a more internal position, the volcanic activity is testified by a limited amount of volcaniclastic debris [55], and by fine-grained pyroclastic materials (silexites [56]).

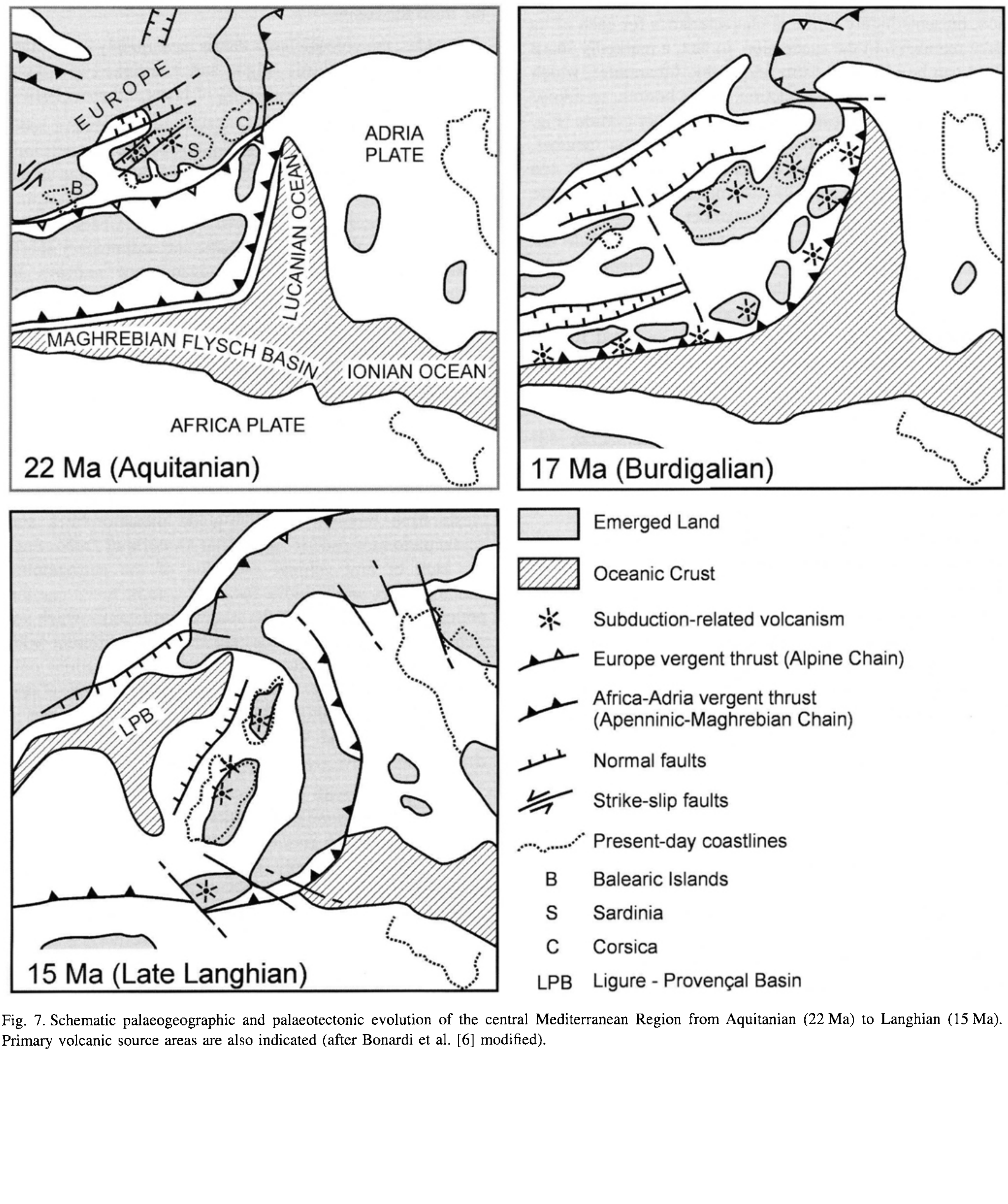

Fig. 7. Schematic palaeogeographic and palaeotectonic evolution of the central Mediterranean Region from Aquitanian (22 Ma) to Langhian (15 Ma). Primary volcanic source areas are also indicated (after Bonardi et al. [6] modified).

Sardinia, where calc-alkaline volcanics, ranging in age from Late Oligocene to Langhian, are widespread [57–59], has been often invoked as the volcanic source area, but the epiclastic character recognised in the thick and coarse-grained volcanogenic deposits cannot fit with this provenance. Besides, the Sardinian calc-alkaline volcanism is characterised mainly by ignimbritic deposits, whereas the studied volcaniclastic terrains have been prevailingly fed by andesite-derived clasts. According to Dewey et al. [60], the *Tufiti di Tusa* Basin is a part of a foredeep located close to the Sardinian Block, but it is separated from this latter by Calabrian crystalline terrains; the authors suggest a kinematic model in which active volcanoes are connected with transform-related tectonics.

We agree with Dewey et al. [60], and we believe that the calc-alkaline volcanic arc, which provided the volcaniclastic materials, should be located close to the Troina–Tusa foredeep, above the already stacked Peloritanian units, which constituted the internal side of the basin itself. This reconstruction agrees well with the petrographic data, which testify an origin from both the basement and the cover of the Peloritanian Units for metamorphic and sedimentary fragments associated with the volcanogenic ones. However, it is to be pointed out that the Peloritanian palaeochain was, at that time, still docked to the Sardinian Block and that the Burdigalian age of the volcanism testified in the volcaniclastic formations of the Maghrebian Flysch Basin suggests a migration of the volcanic activity, which may be due to the subduction plain roll-back. In fact, the calc-alkaline volcanic activity, which occurs in the Sardinian Block starting from the Late Oligocene, appears in the Burdigalian also in the sector of the chain extending from the Peloritani Mts. to the Kabylias, where Burdigalian calc-alkaline lavas and pyroclastics crop out extensively [61–63]. The volcanic activity is also recorded in the Gibraltar Arc, where Lower Miocene volcaniclastic turbiditic formations are present [17–19,64].

It is noteworthy that, during the Burdigalian, calc-alkaline volcanism is widespread in the whole Maghrebian Chain and also in the Southern Apennines [22,23,32]. This volcanism testifies the presence of an oceanic subduction during the Early Miocene, as was first suggested by Guerrera et al. [4], in agreement with the geochemical studies on the Oligo–Miocene calc-alkaline Sardinian volcanism [57]. The volcanic activity confirms that the oceanic crust of the Flysch Basin, and its prosecution in the Southern Apennines, is still present in the Early Miocene. The presence in this epoch of the oceanic crust has not been considered in most previous palaeogeographic reconstructions proposed for the Mediterranean area. In our opinion, Fig. 7, which has been modified after Bonardi et al. [6] mainly as regards the age of the events, well represents the evolution of the Sicilian Maghrebids–Calabria–Peloritani Arc–Southern Apennines system during the Aquitanian–Middle Miocene, between the consumption of the oceanic crust of the Flysch Basin and the continental collision between the Europe–Iberia and Africa–Adria plates.

Acknowledgements

This study was supported by the following grants: MURST–Urbino University Cofin/1997 (resp. V. Perrone) and "Scientific Research"—Urbino University (resp. F. Guerrera). The authors are highly grateful to Professor Michel Durand Delga for his useful revision and to an anonymous referee for suggestions.

References

[1] M. Durand Delga, La Méditerranée occidentale: étapes de sa genèse et problèmes structuraux liés à celle-ci, Mém. H. Sér. Soc. Géol. Fr. 10 (1980) 203–224.

[2] W. Wildi, La chaîne tello-rifaine (Algérie–Maroc–Tunisie): structure, stratigraphie et évolution du Trias au Miocène, Rev. Géol. Dyn. Géogr. Phys. 24 (1983) 201–297.

[3] A. Martín-Algarra, Evolución geológica del contacto entre las Zonas Internas y las Zonas Externas de la Cordillera Bética, Ph.D. Thesis, University of Granada, 1987, pp. 1171.

[4] F. Guerrera, A. Martín-Algarra, V. Perrone, Late Oligocene–Miocene syn- late-orogenic successions in Western and Central Mediterranean Chains from the Betic Cordillera to the Southern Apennines, Terra Nova 5 (1993) 525–544.

[5] G. Bonardi, G. Giunta, A. Messina, V. Perrone, S. Russo, The Calabria–Peloritani Arc and its correlation with Northern Africa and Southern Europe, IGCP Project 276 Newsletter, vol. 6 (special issue), Messina, 1996, pp. 27–86.

[6] G. Bonardi, W. Cavazza, V. Perrone, S. Rossi, Calabria–Peloritani Terrane and Northern Ionian Sea, in: G.B. Vai, I.P. Martini (Eds.), Anatomy of a Mountain Chain: The Apennines and Adjacent Mediterranean Basins, Kluwer Akad. Publ., Dordrecht, The Netherlands, in press.

[7] G. Bonardi, P. de Capoa, B. Fioretti, V. Perrone, Some remarks about the Calabria–Peloritani Arc and its relationships with the Southern Apennines, Boll. Geof. Teor. Appl. 36 (1994) 483–492.

[8] J.P. Bouillin, M. Durand Delga, P. Olivier, Betic–Rifian and Tyrrhenian Arcs: distinctive features, genesis and development stages, in: F.C. Wezel (Ed.), The Origin of Arcs, Elsevier, Amsterdam, 1986, pp. 321–338.

[9] G. Bonardi, P. de Capoa, B. Fioretti, V. Perrone, L'âge des métacalcaires de l'Unité du Frido (région calabro–lucanienne, Italie) et ses implications géodynamiques, C. R. Acad. Sci. Paris 317 (1993) 955–962.

[10] M. Durand Delga, Ph. Rossi, Ph. Olivier, D. Puglisi, Situation structurale et nature ophiolitique de roches basiques jurassiques associées aux flyschs maghrébins du Rif (Maroc) et de Sicile (Italie), C. R. Acad. Sci. Paris 331 (2000) 29–38.

[11] M. Durand Delga, Les unités à Mésozoïque métamorphique d'El Milia à Texenna (Algérie) et leur cadre structural, Bull. Soc. Géol. Fr. 13 (1971) 328–337.

[12] J.P. Bouillin, J. Kornprobst, J.F. Raoult, Données préliminaires sur le complexe volcano-sédimentaire de Rekkada–Metle-tine (ex-Texenna) en Petite Kabylie (Algérie), Bull. Soc. Géol. Fr. 19 (1977) 805–814.

[13] J.-P. Gélard, Géologie du Nord-Est de la Grande Kabylie (un segment des zones internes de l'orogène littoral maghrébin), Mém. Géol. Univ. Dijon (1979) 335.

[14] J. Andrieux, Etude des relations entre la tectonique de compression et les nappes de glissement dans un tronçon de la chaîne alpine, Notes Mém. Serv. Géol. Maroc 235 (1971) 155.

[15] P. Olivier, M. Durand Delga, H. Manivit, H. Feinberg, B. Peybernès, Le substratum jurassique des flyschs maurétaniens de l'ouest des Maghrébides: l'unité de Ouareg (région de Targuist, Rif, Maroc), Bull. Soc. Géol. Fr. 5 (1996) 609–616.

[16] L. Ogniben, Nota illustrativa dello schema geologico della Sicilia nord-orientale, Riv. Mineral. Sicil. 11 (1960) 183–212.

[17] D. Puglisi, R. Carmisciano, Il Flysch di Algeciras (Oligocene–Miocene inf.? Cordigliera Betica): studio petrografico–sedimentologico e confronto con altre unità torbiditiche della catena maghrebide, Boll. Accad. Gioenia Sci. Nat. Catania 25 (340) (1992) 5–23.

[18] U. Chiocchini, R. Franchi, F. Guerrera, W.B.F. Ryan, S. Vannucci, Geologia di alcune successioni torbiditiche cretaceo–terziarie appartenenti ai "Flysch Maurétaniens" e alla "Nappe Numidienne" del Rif Settentrionale, Studi Geol. Camerti 4 (1980) 37–66.

[19] M.N. Zaghloul, F. Guerrera, F. Loiacono, P. Maiorano, D. Puglisi, Stratigraphy and petrography of the Beni Ider Flysch in the Tétouan area (Rif Chain, Morocco), Boll. Soc. Geol. Ital. (in press).

[20] L. Ogniben, Arenarie tipo Taveyannaz in Sicilia, Geol. Rom. 3 (1964) 125–170.

[21] L. Ogniben, Schema introduttivo alla geologia del confine calabro–lucano, Mem. Soc. Geol. Ital. 8 (1969) 453–763.

[22] A. Zuppetta, M. Russo, E. Turco, Alcune osservazioni sulle Tufiti di Tusa nell'area compresa tra Valsinni e Rocca Imperiale (confine calabro–lucano), Boll. Soc. Geol. Ital. 103 (1984) 623–627.

[23] S. Critelli, R. De Rosa, M. Sonnino, G.G. Zuffa, Significato dei depositi vulcanoclastici della Formazione delle Tufiti di Tusa (Miocene inferiore, Lucania meridionale), Boll. Soc. Geol. Ital. 109 (1990) 743–762.

[24] F. Guerrera, M. Mattioli, D. Puglisi, A. Renzulli, P. Santi, F. Veneri, A. Assorgia, K. Balogh, An overview of the Upper Oligocene–Lower Miocene volcanogenic sediments in the Western Mediterranean: what volcanic source areas and geodynamic constraints? Atti Xth Congress R.C.M.N.S. "New lights on Mediterranean Chronology, Tethys–Paratethys Connections", Rom. J. Stratigr. 78 (1998) 43–56.

[25] F.C. Wezel, F. Guerrera, Nuovi dati sulla età e posizione strutturale del Flysch di Tusa in Sicilia, Boll. Soc. Geol. Ital. 92 (1973) 193–211.

[26] F. Guerrera, F.C. Wezel, Nuovi dati stratigrafici sui flysch oligo–miocenici siciliani e considerazioni tettoniche relative, Riv. Mineral. Sicil. 25 (1974) 27–51.

[27] L. Vezzani, G. Lanzafame, E. Ferrara, G. Frazzetta, E. Di Geronimo, T. Amore, Foglio 611 Mistretta della Carta Geologica d'Italia in scala 1:50 000, Servizio Geologica d'Italia, Litografia Artistica e Cartografica, Firenze, 1972.

[28] F. Lentini, L. Vezzani, P. Carveni, B. Copat, M. Grasso, Carta Geologica delle Madonie (Sicilia Centro-settentrionale), Regione Siciliana E.S.A, Litografia Artistica e Cartografica, Firenze, 1974.

[29] L. Vezzani, Note esplicative della Carta Geologica d'Italia: Foglio 611 Mistretta, Servizio Geologica d'Italia, 1974, pp. 37.

[30] S. Carbone, S. Catalano, M. Grasso, F. Lentini, C. Monaco, Carta geologica della Sicilia centro-orientale, S.E.L.C.A., Firenze, 1990.

[31] F. Lentini, S. Carbone, S. Catalano, M. Grasso, C. Monaco, Presentazione della Carta Geologica della Sicilia centro-orientale, Mem. Soc. Geol. Ital. 47 (1991) 145–156.

[32] F. Lentini, Le Unità Sicilidi della Val d'Agri (Appennino Lucano), Geol. Rom. 18 (1979) 215–225.

[33] D. Puglisi, Variazioni composizionali nelle Arenarie del Flysch di Reitano (monti Nebrodi, Sicilia centro-settentrionale), Mineral. Petrogr. Acta 23 (1979) 13–46.

[34] P. Cassola, F. Loiacono, E. Moretti, F. Nigro, D. Puglisi, R. Sbarra, The Reitano Flysch in the northern sector of the Nebrodi Mountains (NE Sicily): sedimentological, petrographical and structural characters, Giorn. Geol. 57 (1995) 195–217.

[35] P. de Capoa, F. Guerrera, V. Perrone, F. Serrano, M. Tramontana, The onset of the syn-orogenic sedimentation in the Flysch Basin of the Sicilian Maghrebids: state of the art and new biostratigraphic constraints, Ecl. Geol. Helv. 93 (2000) 1–15.

[36] L. Amodio Morelli, G. Bonardi, V. Colonna, D. Dietrich, G. Giunta, F. Ippolito, V. Liguori, S. Lorenzoni, A. Paglionico, V. Perrone, G. Piccarreta, M. Russo, P. Scandone, E. Zanettin-Lorenzoni, A. Zuppetta, L'arco calabro–peloritano nell'orogene appenninico–maghrebide, Mem. Soc. Geol. Ital. 17 (1976) 1–60.

[37] G.G. Zuffa, Hybrid arenites: their composition and classification, J. Sediment. Petrol. 50 (1980) 21–29.

[38] G.G. Zuffa, Unravelling hinterland and offshore palaeogeography from deep-water arenites, in: J.K. Leggett, G.G. Zuffa (Eds.), Marine Clastic Sedimentology: Concepts and Case Studies, Graham & Trotman, London, 1987, pp. 39–61.

[39] M. Grasso, F. Guerrera, F. La Manna, R. Maniscalco, E. Moretti, D. Puglisi, F. Vigo, Caratteristiche stratigrafiche, sedimentologiche e petrografiche delle Calciruditi e Calcareniti del Monte Pomiere (*Auct.*) dei Monti Nebrodi (Sicilia centro-settentrionale), Mem. Soc. Geol. Ital. 47 (1991) 115–127.

[40] D. Puglisi, Le successioni torbiditiche cretacico–terziarie della Sicilia nord-orientale nel quadro dell'evoluzione del settore meridionale dell'arco calabro–peloritano e della catena maghrebide siciliana, Giorn. Geol. 49 (1987) 167–185.

[41] F. Loiacono, D. Puglisi, Studio sedimentologico–petrografico del Flysch di Reitano (Oligocene–Miocene inferiore, Sicilia), Boll. Soc. Geol. Ital. 102 (1983) 307–328.

[42] P. Cassola, E. Costa, F. Loiacono, E. Moretti, E. Morlotti, D. Puglisi, G. Villa, New sedimentologic, petrographic, biostratigraphic and structural data on the Reitano Flysch (Maghrebian Chain, Sicily), Riv. Ital. Paleontol. Stratigr. 98 (1992) 205–228.

[43] J.R. Young, in: P.R. Bown (Ed.), Neogene Calcareous Nanofossil Biostratigraphy, Kluwer Akad. Publ., Dordrecht, The Netherlands, 1999, pp. 225–265.

[44] E. Martini, Standard tertiary and quaternary calcareous nanoplankton zonation, in: R. Brönnimann, H.H. Renz (Eds.), Proceedings of the Second International Conference on Planktonic Microfossils, vol. 2, E.J. Brill, Leiden, 1971, pp. 739–785.

[45] H. Okada, D. Bukry, Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation (Bukry, 1973; 1975), Mar. Micropal. 5 (1980) 321–325.

[46] U. Biffi, S.B. Manum, Late Eocene–Early Miocene dinoflagellate cyst stratigraphy from the Marche Region (central Italy), Boll. Soc. Paleontol. Ital. 27 (1988) 163–212.

[47] W.H. Blow, Late–Middle Eocene to Recent planktonic foraminiferal biostratigraphy, in: R. Brönnimann, H.H. Renz (Eds.), Proceedings of the First International Conference on Planktonic Microfossils, Geneva, 1967, vol. 1, E.J. Brill, Leiden, 1969, pp. 199–442.

[48] W.R. Dickinson, C.A. Suczek, Plate tectonic and sandstones composition, Bull. Am. Assoc. Petrol. Geol. 63 (1979) 2164–2182.

[49] W.R. Dickinson, Interpreting provenance relations from detrital modes of sandstones, in: G.G. Zuffa (Ed.), Provenance of Arenites, NATO ASI Series 148, 1985, pp. 333–361.

[50] W.R. Dickinson, Provenance and sediment dispersal in relation to paleotectonics and paleogeography of sedimentary basins, in: K.L. Kleinsphen, C. Paola (Eds.), New Perspectives in Basin Analysis, Frontiers in Sedimentary Geology, 1987, pp. 3–25.

[51] W.R. Dickinson, Interpreting detrital modes of greywacke and arkose, J. Sediment. Petrol. 40 (1970) 695–707.

[52] W.R. Dickinson, L.S. Beard, G.R. Brakenridge, J.I. Erjavec, R.C. Ferguson, K.F. Inman, R.A. Knepp, F.A. Lindberg, P.T. Ryberg, Provenance of North America Phanerozoic sandstones in relation to tectonic setting, Geol. Soc. Am. Bull. 94 (1983) 222–235.

[53] S. Critelli, E. Le Pera, V. Perrone, M. Sonnino, Le successioni silicoclastiche nell'evoluzione tettonica cenozoica dell'Appennino meridionale, Studi Geol. Camerti 1995/2 (1997) 155–165 (vol. spec.).

[54] S. Critelli, The interplay of lithospheric flexure and thrust accommodation in forming stratigraphic sequences of the southern Apennines foreland basin system, Italy, Mem. Accad. Naz. Lincei 10 (1999) 1–71.

[55] D. Puglisi, Le successioni torbiditiche "tardorogene" della Sicilia orientale, Giorn. Geol. 54 (1992) 181–194.

[56] C.R. Lorenz, Les silexites et les tuffites du Burdigalien, marqueurs volcano-sédimentaires: corrélations dans le domaine de la Méditerranée occidentale, Bull. Soc. Géol. Fr. 26 (1984) 1203–1210.

[57] L. Beccaluva, P. Brotzu, G. Macciotta, L. Morbidelli, G. Serri, G. Traversa, Cainozoic tectono-magmatic evolution and inferred mantle sources in the Sardo-Tyrrhenian area, in: A. Boriani, et al. (Eds.), The Lithosphere in Italy, Advances in Earth Science Research, Atti Conv. Accad. Lincei 80 (1989) 229–248.

[58] A. Assorgia, S. Barca, C.A. Spano, Synthesis on the Cenozoic stratigraphic, tectonic and volcanic evolution in Sardinia (Italy), Boll. Soc. Geol. Ital. 116 (1997) 407–420.

[59] L. Lecca, R. Lonis, S. Luxoro, E. Melis, F. Secchi, P. Brotzu, Oligo–Miocene volcanic sequences and rifting stages in Sardinia: a review, Per. Mineral. 66 (1997) 7–61.

[60] J.F. Dewey, M.L. Helman, E. Turco, D.H.W. Hutton, S.D. Knott, Kinematics of the Western Mediterranean, in: M.P. Coward, D. Dietrich, R.G. Park (Eds.), Alpine Tectonics, Geological Society Special Publication, London, vol. 45, 1989, pp. 265–283.

[61] H. Bellon, Chronologie radiométrique (K–Ar) des manifestations magmatiques de la Méditerranée occidentale entre 33 et 1 MA, in: F.C. Wezel (Ed.), Sedimentary Basins of Mediterranean Margins, Elsevier, Amsterdam, 1981, pp. 341–360.

[62] O. Belanteur, H. Bellon, R.C. Maury, A. Ouabadi, A. Coutelle, B. Semroud, M. Megartsi, S. Foucard, Le magmatisme miocène de l'Est Algérois, géologie, géochimie et géochronologie ^{40}K–^{40}Ar, C. R. Acad. Sci. Paris 321 (1995) 489–496.

[63] O. Belanteur, A. Louni-Hacini, H. Bellon, J. Cotten, A. Coutelle, S. Foucard, R. Maury, M. Megartsi, A. Ouabadi, B. Semroud, Le volcanisme littoral d'Algérie: nouvelles données chronologiques et géochimiques, Rapp. 35^{e} Congr. CIESM, vol. 35, 1998, pp. 50–51.

[64] J.M. González Donoso, D. Linares, A. Martín-Algarra, F. Serrano, El complejo tectonosedimentario del Campo de Gibraltar. Datos sobre su edad y significado geologico, Bol. R. Soc. Esp. Hist. Nat. Geol. 82 (1–4) (1987) 233–251.