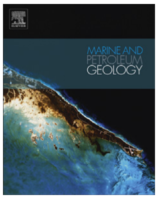
Marine and Petroleum Geology 78 (2016) 291–311

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo



Research paper

The Numidian of Sicily revisited: a thrust-influenced confined turbidite system

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ARTICLE INFO

Article history:
Received 4 April 2016
Received in revised form
28 June 2016
Accepted 16 September 2016
Available online 20 September 2016

Keywords:
Numidian system
Confined turbidites
Active basin
Facies variations

ABSTRACT

Understanding whether a system was unconfined, and deposited on a relatively unstructured basin-floor, or was confined by actively deforming substrate is important for the prediction of turbidite stratigraphy. Here we consider the Numidian turbidite system (Oligocene-Miocene) of Sicily - for many the type example of thick structureless submarine sandstones. New mapping and detailed sedimentology in the Nebrodi and Madonie Mountains (northern Sicily), allied to existing and new biostratigraphic data, challenge conventional interpretations for the Numidian system as a whole. Rather than having been deposited within an unstructured foredeep by relatively unconfined flows, we show that Numidian deposition was confined by active structures. These governed the routing of turbidity currents to create sand fairways and associated facies variations. The controlling structures include thrust-related folds together with inherited basin-floor faults. Existing models suggest that facies variations between adjacent outcrops on Sicily (and elsewhere) result from long-range stratigraphic variations being juxtaposed by later large-displacement thrusts. Our research reveals a much simpler tectonic structure but a more complex stratigraphic arrangement for the Numidian on Sicily - a characteristic of confined turbidite systems.

1. Introduction

Understanding how deep-water clastic successions are controlled by the structure of the sedimentary basins within which they deposited has been driven by a number of case-studies, including rift (e.g. North Sea; Argent et al., 2002; McArthur et al., 2013), salt-related (e.g. Gulf of Mexico; Prather et al., 1998) and foreland basins (e.g. Magallanes basin, Chile; Romans et al., 2011; Shultz and Hubbard, 2005). This helped in the definition of facies distributions, the reconstruction of palaeogeographic scenarios and for creating better arrays of ancient analogues for use in predicting reservoir performance in the subsurface. What is still poorly constrained is how deep-water clastic systems respond to the onset of compressional deformation when being deposited across both inherited and active basin-floor topography. Distinguishing between inherited and syn-sedimentary generated basin-floor relief is important: deep-water systems will respond differently if they passively infill pre-existing topography or if their substrate is actively deforming. Alpine foreland basins provide excellent examples for examining these differences. These ancient systems have provided important analogues for hydrocarbon reservoirs in modern subsurface settings (e.g. Amy et al., 2004; Haughton, 2000; Lucente, 2004; Sinclair and Tomasso, 2002). In these ancient examples syn-depositional bathymetry resulted from a combination of accommodation space inherited from pre-existing rifted continental margins and under-filling where subsidence outstripped sediment supply. It has long been recognised that early models of turbidite deposition in these settings – that considered flows as being largely unconfined, spreading out across open basin floors – are inappropriate and rather that the systems were confined by inherited basin morphology (e.g. Joseph and Lomas, 2004). However, the sensitivity of turbidity currents to changes in gradient and the geometry of confining structures is increasingly used to examine how facies and depositional architecture have responded to active deformation (e.g. Muzzi Magalhaes and Tinterri, 2010; Salles et al., 2014). The aim of this paper is to assess the role of

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http://dx.doi.org/10.1016/j.marpetgeo.2016.09.014

basin structural evolution and its impact on turbidite deposition. Our case study comes from part of the Numidian system of Sicily (Ogniben, 1960). These Miocene strata contain mature quartz sandstones derived from the African craton and delivered into the developing orogens of the Maghreb and southern Apennines, now found in northern Africa and into Italy (Fig. 1; e.g. Benomran et al., 1987; Guerrera and Martín Martín, 2014; Guerrera et al., 2012; Thomas et al., 2010).

The Numidian system of Sicily and the southern Apennines is commonly viewed as being built by unconfined fans (Giunta, 1985; Guerrera et al., 2012 and references therein) deposited on the former continental margin of Africa. During the Oligocene and early Miocene this margin was entering the fledgling Maghrebian-Apennine orogenic belt but is still believed to have retained broad pre-existing bathymetry. The Numidian basin was therefore regarded as an under-filled foredeep, bounded by the African foreland on one side and the developing Maghrebian-Apennine orogenic wedge on the other. In this model for basin configuration, any basin-floor relief has simply been inherited from the pre-existing rifted continental margin of Africa onto which the Numidian was deposited (e.g. Grasso, 2001). Basin-floor faulting in the Numidian substrate have been described by Tavarnelli et al. (2001) but these interpretations have not been incorporated in existing models (Guerrera and Martín Martín, 2014; Guerrera et al., 2012).

The Numidian system is an important analogue for some deep-water sandstone reservoirs found in actively deforming continental margins – where sand quality reflects a mature continental source. It also hosts its own hydrocarbons, well known since the 1950's, including the gas field at Gagliano on Sicily discovered by Agip in 1954 and exploited since 1962 (Coltro, 1967; Fabiani, 1952; Granath and Casero, 2004; Pieri, 2001).

Here we challenge the accepted interpretations of the Numidian as being broadly unconfined. New mapping, sedimentological and structural studies by the present authors demonstrate that turbidity currents interacted with both inherited and active structures on the ancestral continental margin of Africa. We outline the evidence for this deduction and develop the consequences for understanding not only the context and architecture of the Numidian system of Sicily but also the tectonic evolution of the Maghrebian orogenic belt. In addition, we outline the key controls on turbidite deposition over an actively deforming substrate that has applications for prediction of sandstone distribution in similar basins elsewhere in the world.

2. Setting

The Maghrebian chain is a segment of the Alpine orogenic system developed as a result of the convergence between the

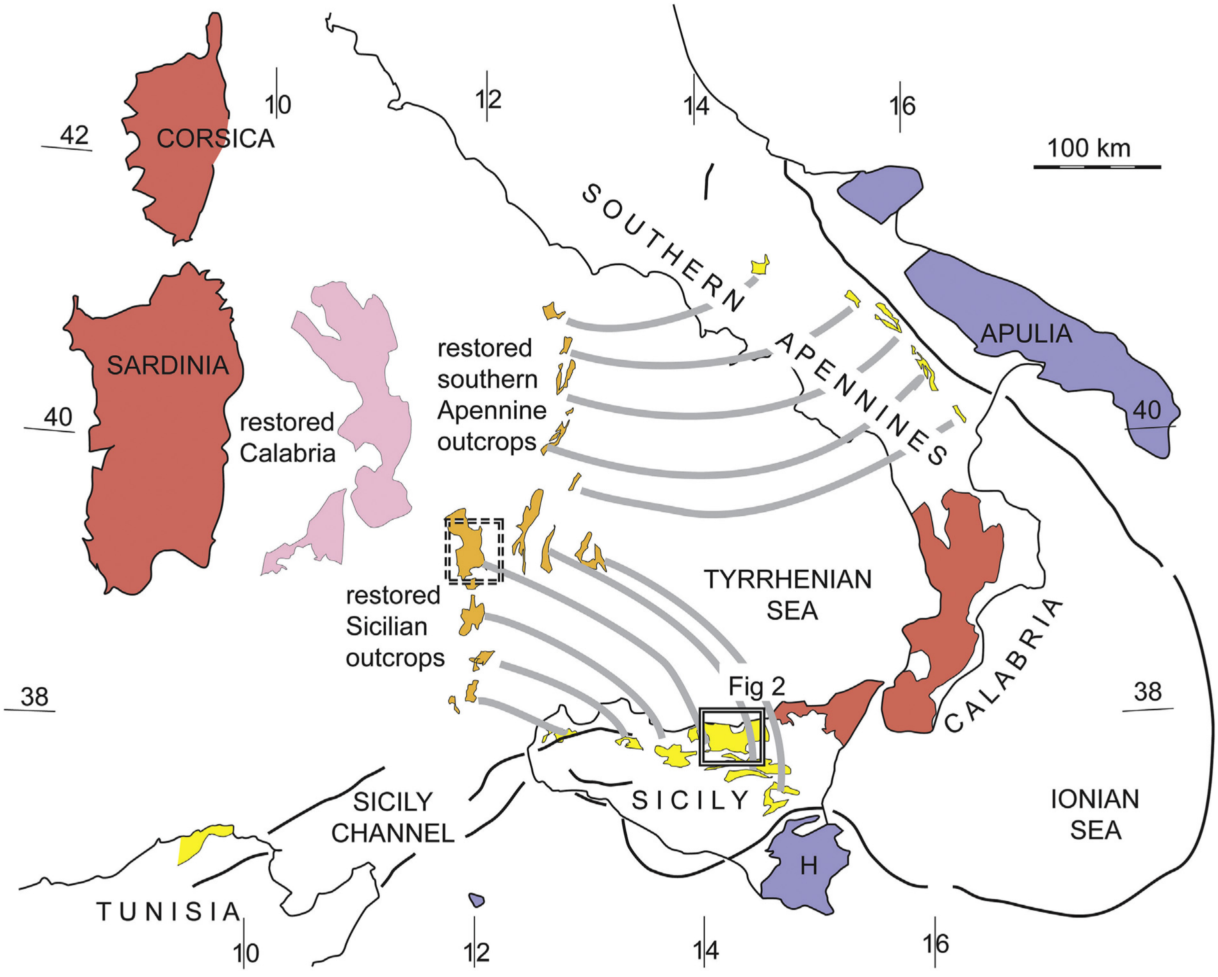


Fig. 1. Setting of the Numidian outcrops in the central Mediterranean. The outcrops in Sicily have experienced a c. 100 CW rotation since deposition while those in the Southern Apennines have experienced a similar CCW rotation (Speranza et al., 2003). The restored positions recover these rotations and show the outcrops ahead (E) of the restored basement terrane of the Calabrian arc. These Numidian outcrops (and their underlying thrust sheets) have been swept onto the orogenic foreland (blue areas; H – Hyblean platform). Boxed area is Fig. 2 (restored as dashed box). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

European and Africa-Adria plates during the late Cretaceous to Pleistocene (Elter et al., 2003). The collisional belt consists of distinct units of the African palaeo-margin and Tethys which include carbonate rocks, oceanic to quasi-oceanic deposits and successive Tertiary siliciclastic sequences that represent the fills of foredeep and thrust-top basins (Lentini et al., 1995). The Numidian system (Ogniben, 1960), classically ascribed to the late Oligocene - early Miocene, represents the earliest foredeep deposits (Grasso, 2001). The succession is composed of sand-rich turbidites sourced from the North African craton (reviewed by Thomas et al., 2010). In regional studies through southern Italy and Sicily, the Numidian is considered to have accumulated exclusively within a foredeep basin alone (Guerrera et al., 2012, 2005; Nigro and Renda, 2000; Pescatore et al., 1987), strictly ahead of then-active thrust structures. All outcrop locations are now located within thrust systems and therefore it is generally assumed that Numidian deposits provide a local older age bracket for the onset of thrusting (Bello et al., 2000; Bianchi et al., 1987; Grasso, 2001). In general terms, this means that those deposits in the foredeep ahead of an active thrust formed successions distinct from broadly coeval deposits that accumulated within thrust-top basins. This is a deduction that will be challenged below.

Here we focus on the Nebrodi and Madonie Mountains of Sicily, a region that contains the greatest outcrop expanse of Numidian strata in the central Mediterranean (Fig. 2a). The area includes sites described by Thomas and Bodin (2013) and it is covered by geological maps of various vintages (Lentini and Vezzani, 1974; Servizio Geologico D'Italia, 2012). These studies have set up various stratigraphic schemes for the upper Oligocene - lower Miocene strata that have been used in regional reviews (e.g. Catalano et al., 1996; Guerrera and Martín Martín, 2014; Guerrera et al., 2012). Existing cross-sections consider the area to form a major imbricate thrust stack that formed after deposition of the Numidian strata (Bello et al., 2000; Bianchi et al., 1987). Thus the original stratigraphy is considered to be entirely modified by later deformation in a regional scale. We suggest that the current structural interpretation is incorrect and that post-depositional structural modification of the relationship between Numidian stratigraphic packages in northern Sicily is relatively minor. Much of our account is based on new fieldwork. Detailed field mapping

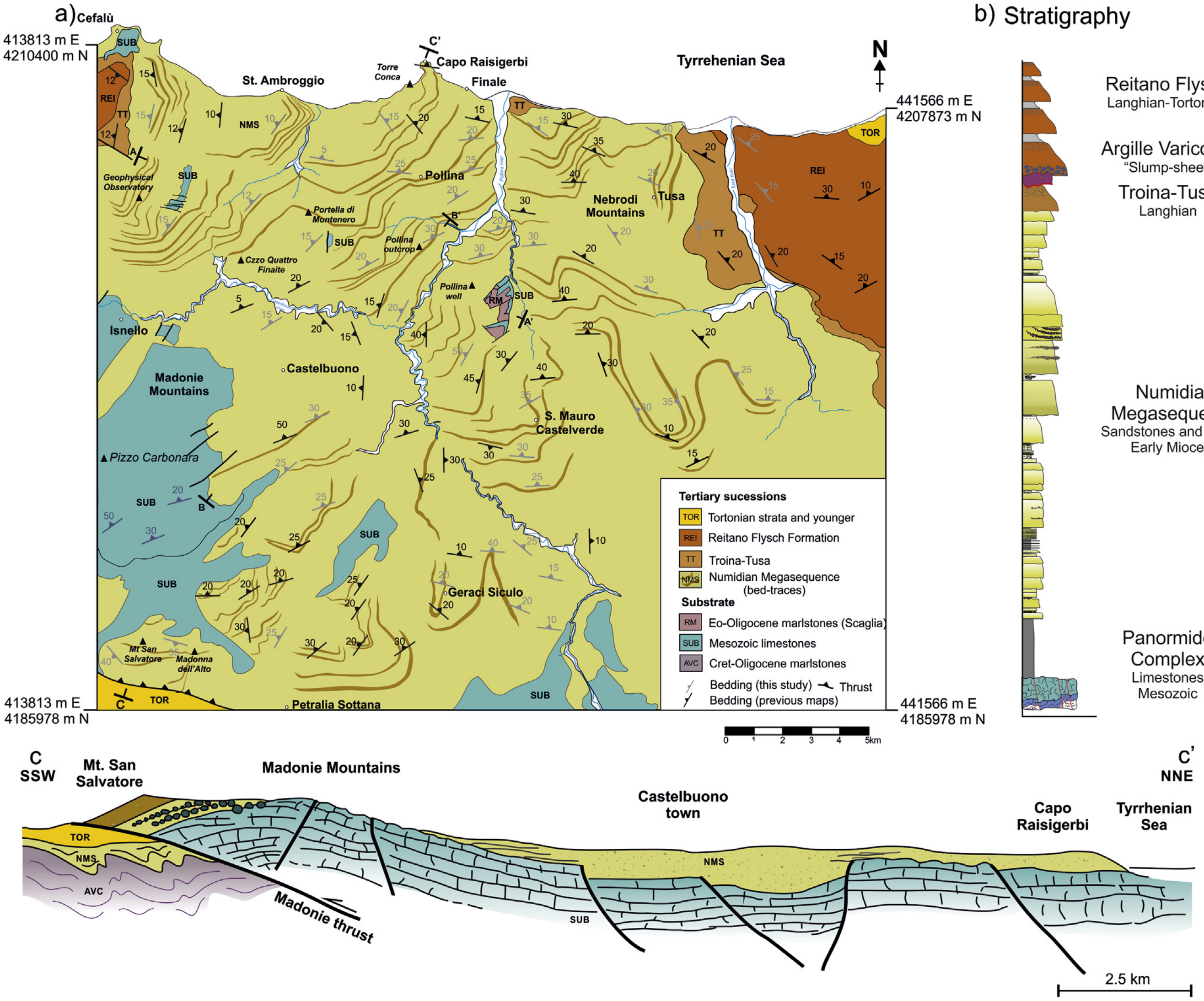


Fig. 2. a) Geological map of the Nebrodi-Madonie area showing the main lithological units mapped in this study, including the continuity of prominent Numidian bed-sets. A-A' (Fig. 10) and B-B' (Fig. 11) cross section traces; b) Simplified generalised stratigraphic column for the Nebrodi-Madonie area showing the complete section up to the younger Reitano succession; c) Simplified regional cross-section (C-C' shown on Fig. 2a) showing the continuity of Mesozoic substrate beneath the Nebrodi-Madonie area, together with their southward emplacement on an underlying thrust.

on the Numidian turbidites was undertaken using a combination of traditional and digital mapping techniques (using Midland Valley's FieldMove application). Locations of key outcrops are given in UTM coordinates in the text. We also consulted, but strongly modified, published geological maps of 1:50 000 scale (Lentini and Vezzani, 1974; Servizio Geologico D'Italia, 2012), together with high resolution satellite images. Most of the individual bed-sets were traced in the field, and generated digital lithological boundaries onto the base map. On inaccessible outcrops, the lateral continuity of the sandstone bed-sets was established using high resolution satellite images and digital topographic data. However, modern slope processes serve to obscure some of the bed-set continuity, especially when finer-grained. Consequently only those bed-set traces with which we have most confidence are shown on Fig. 2a. Our new mapping essentially falsifies structural interpretations for the area that invoke multiple, steep imbricate thrusts (e.g. Bianchi et al., 1987). The mapping also challenges biostratigraphic schemes for the strata themselves, as discussed below.

Traditionally, the age of the Numidian system of Sicily and mainland Italy has been considered to span late Oligocene to early Miocene (Carbone and Grasso, 2012). Precursor sedimentation is represented by the so-called Scaglia facies (or “Argille Varicolori”) which is Late Cretaceous to Eocene in age (Catalano et al., 1974; Grasso et al., 1978). However, as discussed below, earlier Cretaceous carbonates generally form the substrate to Numidian rocks in our study area of northern Sicily (Nigro and Renda, 2000) which do not assist in better-defining the age of the Numidian rocks.

2.1. *Biostratigraphy of Numidian*

Several studies have used biostratigraphy of the Numidian succession to constrain its age (e.g. Carbone and Grasso, 2012; Sami et al., 2010; Servizio Geologico D'Italia, 2012; Wezel, 1970). Although well exposed sections of fine-grained sediments are common in the Nebrodi and Madonie area, samples in general contain limited faunal assemblages and specimens are commonly poorly preserved. As described by De Capoa et al. (2004), turbidite systems commonly show significant reworking processes and autochthonous taxa are scarce and badly preserved, resulting in poor biozonal resolution. The bad preservation degree of foraminifers in most samples prevented the collection of quantitative data and the age determination was based on the presence of the youngest foraminiferal and/or nannofossil marker species. In attempt to narrow the age for the Numidian succession of Sicily, we collected more than 100 samples, tied to logged sections, from various sites within the study area (Supplementary material – Biostratigraphy_sample locations.kmz here). The sampling locations were carefully selected according to the three Numidian lithostratigraphic units published in the previous geological maps. These units include the Numidian sandstone-rich unit itself (locally termed the Geraci Siculo Member (Servizio Geologico D'Italia, 2012)) together with two distinctly finer-grained facies termed the Argille di Portella Mandarini and the Castelbuono Marls. According to existing stratigraphic schemes, these lithostratigraphic units represent different palaeogeographic settings and have different ages (Carbone and Grasso, 2012; Servizio Geologico D'Italia, 2012). To target these differences, we have preferentially sampled in vertical sections, with 1 m spacing between the samples, allied to the sedimentary logs. In less continuous sections, isolated samples were collected with information about stratigraphic position, location, and lithology. Unfortunately only 33 samples could be dated according to their calcareous plankton assemblages (foraminifera and nannofossils). From the total of 33 samples, 3 came from the early siltstones (Argille di Portella Mandarini: assigned to the Late Oligocene by Servizio Geologico D'Italia (2012)), 13 from finer-grained parts of the main Numidian unit (Geraci Siculo: assigned to the Late Oligocene – early Miocene, Servizio Geologico D'Italia (2012)) and 17 from the overlying deposits (Castelbuono Marls; assigned to the Late Burdigalian, Servizio Geologico D'Italia (2012)) (Supplementary material – Table A1 here). The samples were processed and analyzed at the Department of Biological, Geological and Environmental Sciences of the University of Catania. Samples for planktonic foraminiferal analysis were washed in fresh water through a 63 μm sieve and dried at 50 °C in oven. Planktonic foraminifers were distinguished at specific or supra-specific level. Calcareous nannofossils associations were only recovered from outcrops around Castelbuono town and on the SE slopes of the Madonie mountains. Samples from these two broad localities yielded quantitative counts of the relevant genera (*Sphenolithus* and *Helicosphaera*) for establishing biozonal markers for the considered time intervals.

The new biostratigraphic data are summarized in Table 1. All samples contain a faunal association of early Miocene age (late Aquitanian to late Burdigalian) indicating a bracket between biozones MMi2b/MMi3 according to the Mediterranean foraminiferal zonations of Foresi et al. (2014) and Iaccarino et al. (2007). However, samples from Castelbuono marls (Servizio Geologico D'Italia, 2012) that combine foraminifera and calcareous nannofossil assemblages show a better age constrain. The faunal assemblage consists of G*lobigerinoides trilobus*, *Globoquadrina dehiscens* and *Paragloborotalia acrostoma* (planktonic foraminifera), and *Sphenolithus belemnos*, *Sphenolithus disbelemnos*, *Helicosphaera ampliaperta* and *Helicosphaera carteri* (calcareous nannofossils). These conform to biozones MMi2b/MMi2c and MNN3a/MNN3b, as defined respectively in the Mediterranean foraminiferal zonations of Foresi et al. (2014) and Iaccarino et al. (2007) and calcareous nannofossils zonations of Fornaciari and Rio (1996). These are placed in the mid-Burdigalian (Table 1). The samples from Argille di Portella Mandarini (Servizio Geologico D'Italia, 2012) conform to biozones MMi2b/MMi2c (planktonic foraminifera) and MNN3a (calcareous nannofossil) and are also dated as mid-Burdigalian (Table 1). This latter attribution is supported by the recognition of specimens of G*lobigerinoides trilobus*, *Globoquadrina dehiscens* and *Paragloborotalia acrostoma* within the planktonic foraminifera assemblage. Samples with this foraminifera assemblage were also found to contain the calcareous nannofossil *Sphenolithus belemnos* in association with *Sphenolithus disbelemnos*, *Helicosphaera ampliaperta* and *Helicosphaera carteri*.

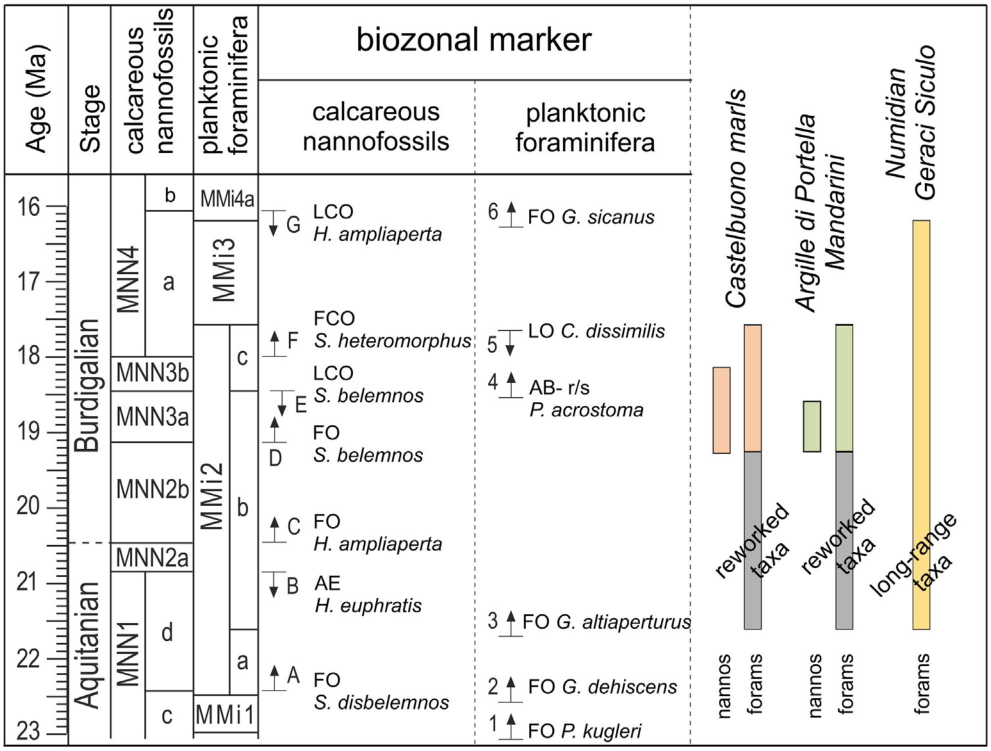
Even though the Numidian samples present a wider time interval (Aquitanian to late Burdigalian) and long-ranging non-diagnostic taxa when based upon planktonic foraminifera alone, the Argille di Portella Mandarini stratigraphically underlies the Numidian succession in the study area. This which means that ages older than mid-Burdigalian from the Numidian samples have no chronological significance. These new data suggest that the Numidian turbidites of the Nebrodi and Madonie region have a rather narrow and consistent age range. The faunal data are consistent with broadly coeval deposition of the different lithofacies – there are no significant chronostratigraphic differences between the three lithostratigraphic units defined by previous workers (as discussed above). We will incorporate the different units in a facies scheme (see below) but hereafter group them into a single Numidian succession.

2.2. *Younger strata*

The Numidian succession of northern Sicily is capped by the so-called Reitano Flysch (Fig. 2b), a succession of turbidites derived from relatively immature source terranes within the developing Maghrebian orogen (Balogh et al., 2001; Cassola et al., 1995, 1992).

Table 1

Bio-chronostratigraphic framework adapted for the present work and depositional intervals recognised in the studied samples. The samples from Castelbuono marls and Argille di Portella Mandarini (Servizio Geologico D'Italia, 2012) combine foraminifera and calcareous nannofossil assemblages. The faunal assemblage for Castelbuono marls conform to biozones MMi2b/MMi2c (planktonic foraminifera) and MNN3a/MNN3b (calcareous nannofossils), and correspond to mid-Burdigalian age. The faunal assemblage for Argille di Portella Mandarini (Servizio Geologico D'Italia, 2012) conform to biozones MMi2b/MMi2c (planktonic foraminifera) and MNN3a (calcareous nannofossils), and correspond to mid-Burdigalian. The Numidian shales (Geraci Siculo) present a wider time interval (Aquitanian to late Burdigalian) according to planktonic foraminifera, but the faunal assemblage older than mid-Burdigalian represents long-range non-diagnostic taxa and has no geological significance once the Argille di Portella Mandarini stratigraphically underlies the Numidian succession in the study area. The Mediterranean nannofossil zonation includes Fornaciari and Rio (1996) and Iaccarino et al. (2011). The Mediterranean planktonic foraminifera zonation includes Foresi et al. (2014) and Iaccarino et al. (2011, 2007); Bio-event chronology from: Backman et al., 2012; Di Stefano et al., 2011; Foresi et al., 2014; Lourens et al., 2004; Turco et al., 2011; Wade et al., 2011. FO = First Occurrence; LO = Last Occurrence; AB - r/s = Acme Beginning-Coiling change from random to prevalently sinistral; AE = Acme End; FCO = First Common Occurrence; LCO = Last Common Occurrence.



In this regard the Reitano forms a turbidite system that is distinct from the Numidian. No mixed successions of Numidian quartz-arenites and micaceous sandstones of Reitano type deposits (Grasso et al., 1987; Guerrera et al., 1986) are known from our study area, indicating that, in the Nebrodi area at least, Numidian deposition had finished prior to the influx of orogen-derived material. The Reitano Flysch, and therefore the end of Numidian deposition, is dated as "not older than Langhian" (Critelli, 1991; De Capoa et al., 2004, 2000; Grasso et al., 1999), even if it commonly contains reworked Oligocene and lower Miocene faunal assemblages (Guerrera and Wezel, 1974; La Manna et al., 1995; Lentini et al., 2000). These relationships are consistent with the Numidian biostratigraphy presented above. We conclude that, in the Nebrodi region, the influx of African-derived quartz sand was restricted to Burdigalian times. Subsequently, in the Langhian and younger times, sedimentation came from a non-African hinterland. Any residual African-sourced turbidity currents were presumably directed away from the palaeo-Nebrodi region. We reserve further discussion on the regional evolution of the Numidian sand fairway in the central Mediterranean to a later paper.

3. Substrate

The substrate to the Numidian succession crops out along the western flank of the Nebrodi region in the Madonie hills. The main exposure is centred on Pizzo Carbonara (415092 m E; 4194824 m N, Fig. 2a). This substrate consists of Cretaceous platform carbonates – comprising the so-called Panormide tectono-stratigraphic terrane (Ogniben, 1960; Trevisan, 1960). These carbonates also crop out in small inliers within the Nebrodi region (Fig. 2a). One of the inliers, at an abandoned quarry at Portella di Montenero (421939 m E; 4202770 m N, Fig. 3), has been described by Dewever et al. (2010). This location exposes an unconformity between the platform limestones and the overlying Numidian turbidites (Fig. 3a). The limestones at the unconformity show palaeo–karstic features, and the unconformity surface is irregularly incised (Fig. 3b). These relationships indicate that the Panormide platform, at least locally, had been uplifted to become emergent before it subsided significantly below sea-level to receive Numidian turbidites.

It is not possible to establish the precise timing of emergence and subsequent subsidence from Portella di Montenero quarry. However, another inlier, close to the village of San Mauro Castelverde (427960 m E; 4200786 m N, Fig. 4a, b) provides further insight. At this location, Cretaceous platform carbonates also have a karstified upper surface characterized by palaeo-caves filled by beige mudstones indicative of palaeo-karst fills. The top of the limestones retains an irregular unconformity surface (Fig. 4c) and here the palaeo-relief is filled by cherty red marlstones termed "Scaglia". The Scaglia marlstones (Fig. 4d) are generally interpreted to represent marine conditions with deposition significantly

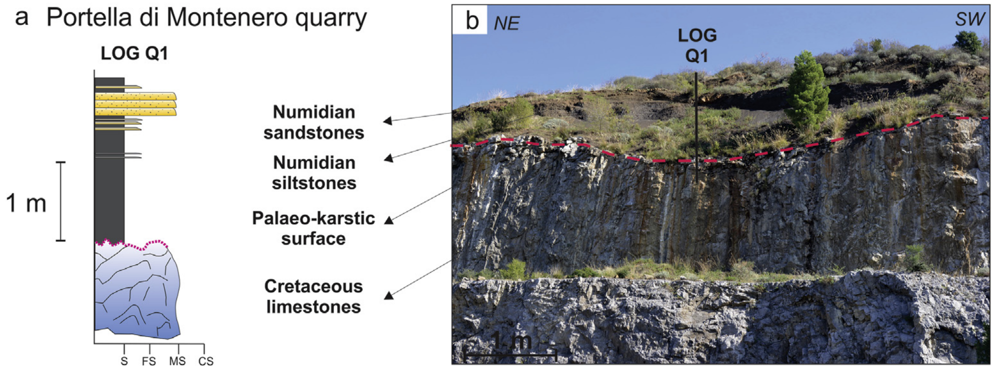


Fig. 3. a) Sedimentary log Q1 showing a short section of Numidian turbidites directly overlying the palaeo-karstic surface on top of Mesozoic limestones (substrate) at the Portella di Montenero quarry; b) One face of the quarry, showing the palaeo-karstic surface at the top of the limestones together with the location of log Q1.

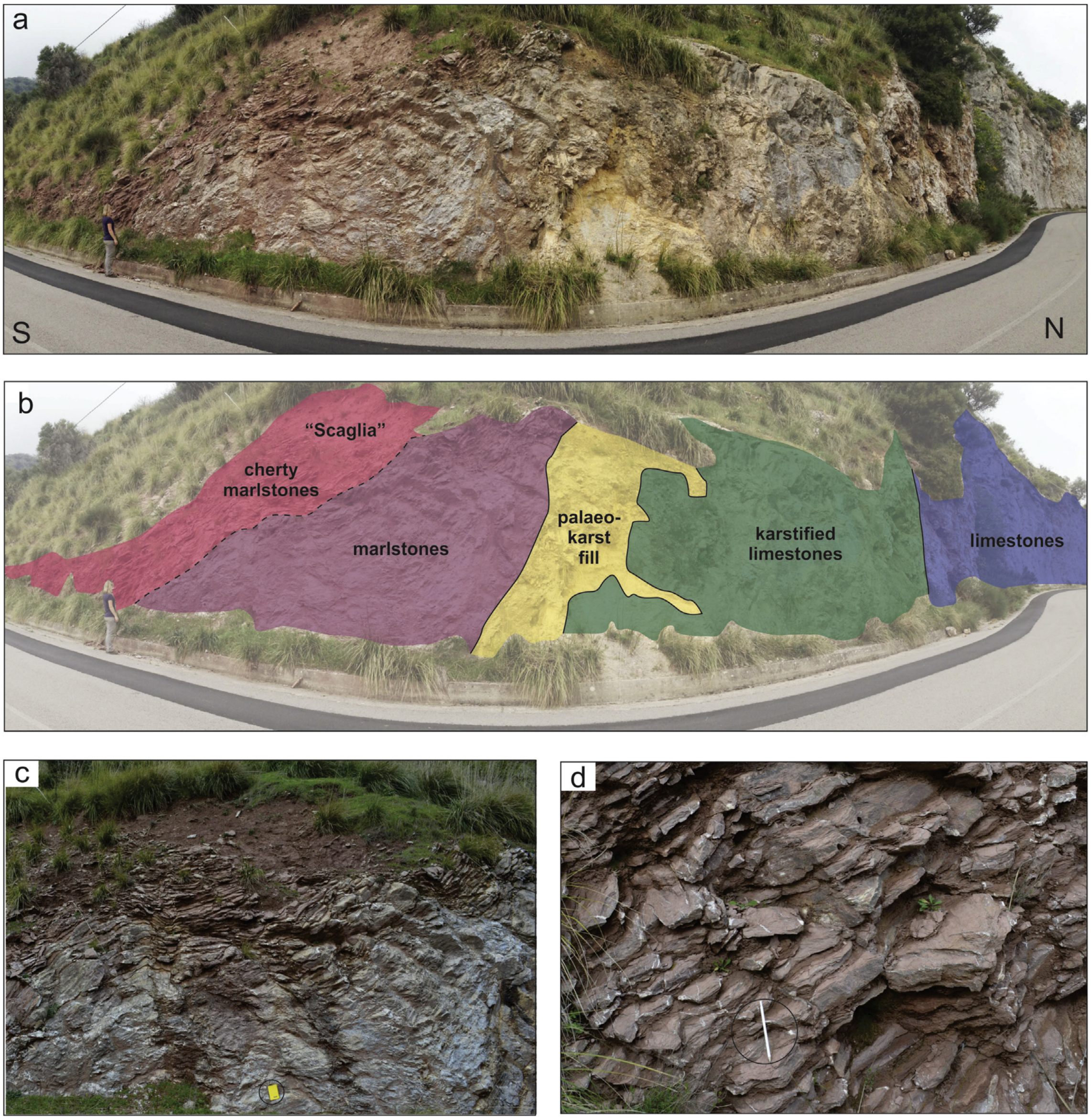


Fig. 4. a) View of the road section at San Mauro Castelverde; b) Annotated photograph of the road section shown in Fig. 4a. The succession dips towards the south; limestones crop out at the base of the section, followed by a zone of intensively karstified limestones and mudstones characteristic of palaeo-karst fill. The palaeo-karstic surface is covered by red marlstones that show a gradual transition to cherty marlstones (relatively deep-water deposits); c) Detail of the irregular palaeo-karstic surface on top of the limestones and red cherty marlstones (field book as scale); d) Cherty red marlstone of "Scaglia type" (pencil as scale). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

deeper than storm wave-base with very limited clastic input (Grasso et al., 1978; Lentini and Vezzani, 1974), and it is these strata that form the immediate substrate to the Numidian turbidites around San Mauro (Grasso et al., 1978). The stratigraphic age of the Scaglia determined elsewhere in northern Sicily is latest Cretaceous to Eocene (Carbone and Grasso, 2012; Grasso et al., 1978; Lentini and Vezzani, 1974).

Taking the two inliers (Portella di Montenero quarry and San Mauro) together, it is evident that the basin-floor onto which the Numidian turbidites accumulated contained distinctly different substrates, and that these variations were established after the development of the widespread carbonate platform of the Panormide. This platform was restructured, manifest by differential uplift, emergence, erosion and karstification, and then subsided before Numidian deposition. These variations are best explained by differential uplift of blocks and basin areas, sometime between the late Cretaceous and Miocene. High-standing fault blocks within this restructured basin have retained the unconformity between Numidian turbidites and its substrate, as documented in Portella di Montenero quarry. The intrabasinal lows received the cherty red marls as seen in San Mauro Castelverde. It is not clear from the location of the inliers whether deformation associated with platform restructuring and differential subsidence continued during Numidian deposition. Outcrop locations elsewhere in our study area, discussed later, do however provide evidence for active deformation during Numidian deposition.

4. Lithofacies of the Numidian megasequence

There are several competing stratigraphic schemes for the Miocene strata on Sicily and adjacent areas. According to more consistent age within the different facies in the Numidian succession, here we chose to group the strata that post-date the pre-Numidian substrate described above into a single “Numidian megasequence”. We now discuss the constituent lithofacies of this megasequence. Although outcrop within the Nebrodi-Madonie hills is strongly biased towards the coarser-grained facies, soil and worked fields provide reasonable control on underlying geology. Type locations and field descriptions are provided for each of the lithofacies and, in our interpretation, we draw parallels with other facies classification schemes for deep-water sediments. The lithofacies of the Numidian Megasequence are divided into 3 main groups, which were described in detail below.

4.1. Group A – Carbonates

4.1.1. Lithofacies A1 – Carbonate breccias

This lithofacies of 10–30 m thick carbonate breccias crops out extensively in the southern part of the Madonie Mountains (417526 m E; 4188210 m N, Fig. 5a). Our type area, where the breccias form prominent cliffs, lies on the SE slopes of Monte San Salvatore NW of Petralia Sottana village. The cliffs define parts of mappable units that are laterally continuous for over one kilometre. These units comprise bed-sets with individual beds generally 0.5 m–3 m thick. The carbonate breccias are clast-supported, comprise angular to sub-angular clasts and lack a fine-grained matrix. The lithofacies is very poorly sorted: clast sizes vary from coarse sand up to boulders several metres in diameter, although generally clasts are a few centimetres in diameter. Lithoclasts are exclusively carbonate (limestones with rare dolostone), chiefly packstones and grainstones. We found no evidence for biological action on these clasts, such as boring or algal coatings. Although the internal structure of beds generally appears chaotic. There is very weak alignment of larger clasts with long-axes sub-parallel to bedding together with some weak normal grading in some units. The basal boundary of the bed-sets of carbonate breccias shows incisional relief of 10–15 cm into fine-grained units (described below). The top of each bed-set is abrupt. Bed-set tops and bases are generally subparallel so that they define, on the kilometre-scale, tabular units. Internally, bedding is generally sub-parallel to bed-set bounding surfaces.

This lithofacies generally crops out in close proximity to the Cretaceous platform carbonates that form much of the substrate to the Numidian megasequence. NW of Petralia Sottana, bed-sets of carbonate breccia can be mapped back to the substrate in the Madonie Mountains (Lentini and Vezzani, 1974). Since all carbonate breccia fragments are lithoclasts of platform-facies carbonates, we infer that this lithofacies was derived from submarine wasting of lithified platform strata. The absence of biological activity on clast grain boundaries may suggest that the breccias derived from submarine mass wasting events, rather than be derived from coastal erosion. We deduce that the breccia bed-sets record repeated rockfalls down an active submarine slope: the absence of sandy or muddy matrix between the carbonate clasts effectively precludes transportation by other forms of subaqueous gravity flows such as turbidity currents or debris flows. Oversized blocks, several 10's of m across, found in the type area near Petralia Sottana (previously mapped by Lentini and Vezzani, 1974) presumably represent individual slide-blocks. The repeated occurrence of rock fall deposits at individual locations strongly suggests recurrent slope instability and active deformation of the Panormide platform during the accumulation of this lithofacies. Note that this lithofacies constitutes part of the Argille di Portella Mandarini of some previous workers (e.g. Lentini and Vezzani, 1974).

4.2. Group B – Quartz arenites

4.2.1. Lithofacies B1 – Pebbly conglomerates

Our type section for this lithofacies is located at Capo Raisigerbi (425194 m E; 4209302 m N, Fig. 5b), and corresponds to lithofacies FA-1 of Thomas and Bodin (2013). Pebbly conglomerates form parts of cliff sections but generally constitute beds of up to 1 m thickness. Grain sizes are locally up to 7 cm in diameter although are generally 1–2 cm. The matrix is generally coarse to very coarse quartz sand. Sorting is generally poor, with weak normal grading. These conglomerates are very poorly structured although grain alignment, sub-parallel to bedding, is locally evident. Both the matrix and the pebbles are almost exclusively composed of quartz (> 99%). The base of the pebbly conglomerates weakly incise (maximum 10 cm) into underlying beds within the Numidian megasequence. In the type area at Capo Raisigerbi, the conglomerates bodies are lenticular, interpreted by Thomas and Bodin (2013) as submarine channel deposits. However the lateral extent of these units is disrupted by post-depositional faults in their study location making such interpretations difficult to support on geometric grounds alone. So while the facies is consistent with channel-fill settings, the architectural evidence remains somewhat conjectural.

4.2.2. Lithofacies B2 – Well sorted coarse sandstones

This lithofacies has the typical characteristics ascribed to Numidian sandstones in the literature (e.g. Johansson et al., 1998; Stow and Johansson, 2000). It crops out extensively in central-north Sicily as cliff-forming units tens of metres thick. Our type section for this lithofacies is located on the sea cliffs of Torre Conca (424504 m E; 4208571 m N, Fig. 5c), and typically forms bed-sets mappable for several km throughout the Nebrodi area. Bed-set packages comprise individual beds 0.5–2 m in thickness. Composite bed-sets of amalgamated sandstones can achieve thicknesses of tens of metres (9 m in our type area). This lithofacies is characterized by coarse to medium grain size, well-sorted and

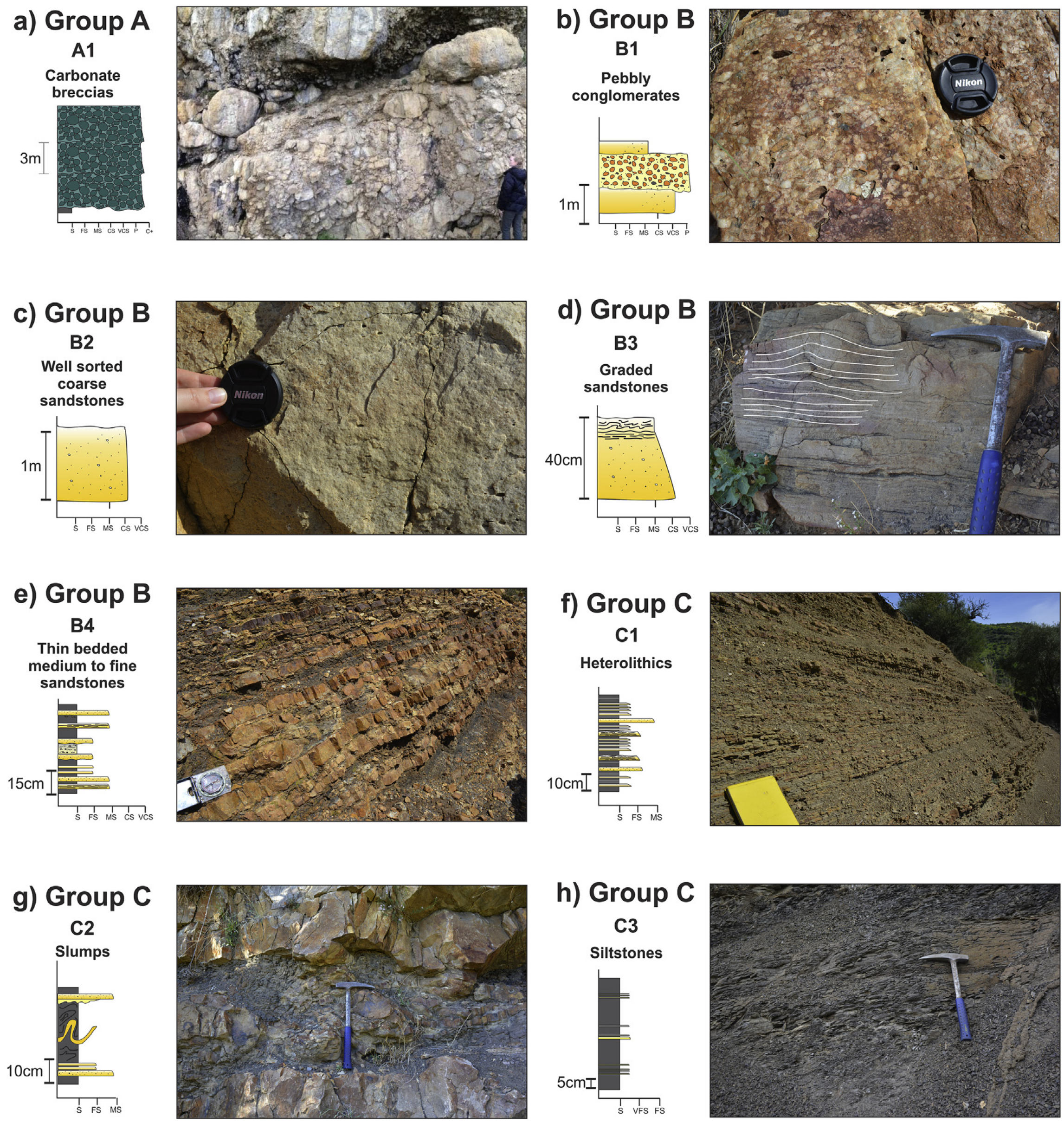


Fig. 5. Lithofacies of the Numidian megasequence. a) Group A represents carbonates lithofacies and it includes carbonate breccias (Lithofacies A1); b) Group B represents quartz arenites lithofacies and it is subdivided in 4 lithofacies including pebbly conglomerates (Lithofacies B1); c) well sorted coarse sandstones (Lithofacies B2); d) graded sandstones (Lithofacies B4); e) thin-bedded fine to medium sandstones (Lithofacies B4); f) Group C represents silty successions and it is sub-divided in 3 lithofacies including heterolithics (Lithofacies C1); g) slumps (Lithofacies C2) and h) siltstones (Lithofacies C3).

almost exclusively quartz (> 99%). Outsized clasts of granule and up to 1 cm pebble-sizes are commonly dispersed through beds as are small (1–2 cm) mud clasts. The uniformity of grain size and composition renders identification of internal structure to the beds difficult to determine, especially on inland outcrops. However, in our type area, internal weak lamination and banding is evident, together with dish and pillar structures indicative of syn-deposition dewatering. These beds preserve weak normal grading. The basal contact of the sandstones can be slightly erosive (incisional relief of max 4 cm) or sharp. Bed tops are sharp or commonly obscured by amalgamation. Sharp bed tops are generally exposed when coarse sandstones are overlain directly by siltstones. In these cases, contacts display a distinct grain-size jump. We infer that this is caused by the bypassing of the intermediate grain size fraction, carried by the causative turbidity current. The coarse sandstones vary in thickness laterally but in general they display a tabular geometry.

We interpret this lithofacies as deposits along the main flow axis of the turbidity currents. The bed structure suggests substantial flow bypass during deposition. The general tabular nature of these strata suggests that they were not restricted to distinct channels but stacked to form, presumably highly elongate lobes. The general bypassing character of the deposit requires the flows to be confined by either aggradational or incisional channels or, more probably, by basin-floor topography.

4.2.3. *Lithofacies B3 — Graded sandstones*

The type section for this lithofacies is located at St. Ambrogio village (420788 m E; 4207640 m N, Fig. 5d), in the north of Sicily. Graded sandstones form cliffs and ridges and do not occur extensively in the Numidian succession and are always associated with well-sorted coarse sandstones of Lithofacies B2. Bed-sets comprise individual beds of 10 to maximum 90 cm. Composite bed-sets of amalgamated sandstones can be up to 2 m thick. This lithofacies is characterized by normally-graded sandstones of coarse to fine grain size. In general finer grained sands present slightly better sorting than the coarse sands. These sandstones are composed almost exclusively of quartz grains. Grains are rounded to sub-rounded. In general, the basal part of the sandstones displays spaced sub-horizontal lamination that changes upwards to better developed parallel laminated sandstones. These laminated intervals follow the overall fining of the grain size. In rare cases, parallel laminated units are followed by ripples, and associated convolute lamination. Rippled intervals rarely exceed thicknesses of 10 cm. The basal contact of the graded sandstones can be slightly erosive but in general is planar. The bed tops are sharp or slightly wavy in the rippled or convoluted intervals. Bed-sets of graded sandstones form tabular units. This lithofacies can be interpreted to be deposited by locally waning turbidity currents. These may have been smaller, at their depositional sites, and thus behave as generally unconfined, with respect to those that deposited Lithofacies B1 and B2.

4.2.4. *Lithofacies B4 – Thin-bedded medium to fine sandstones*

This lithofacies crops out in central-north Sicily and is interbedded with the well-sorted coarse sandstones (Lithofacies B2). Thin-bedded medium to fine sandstones tend to crop out poorly on open hillsides and so the best exposures are found in road sections. Our type section for this lithofacies is located in the road near San Mauro Castelverde (427748 m E; 4199157 m N, Fig. 5e). It comprises grey to brown laminated siltstones interbedded with sandstones of 1–20 cm thickness. In rare cases, thin sandstone beds are amalgamated and the composite bed-sets achieve maximum thicknesses of around 25 cm. The sandstones are medium to fine grained, well-sorted and composed exclusively of quartz grains. Medium to fine sandstones are ungraded or show weak normal grading. In some cases, the beds are parallel laminated and have convolute lamination towards the top. Convoluted intervals are limited to 3 cm in thickness. Convolute bed tops are slightly wavy. In all other cases, bed tops are sharp and do not grade out into overlying strata. Bed bases are sharp or slightly erosive (max 2 cm incisional relief) and commonly loaded. In the type area, some of the sandstones beds are disrupted, folded and encased in debritic siltstones. Thin-bedded medium to fine sandstones are tabular and they crop out as concordant units with the coarse sandstones (Lithofacies B2). We interpret this lithofacies as representing deposits from the edges of turbidity currents that are otherwise traversing the basin.

4.3. *Group C – Silty successions*

4.3.1. *Lithofacies C1 – Heterolithics*

This lithofacies occurs extensively around the town of Castelbuono. Within our study area it is rather poorly exposed, with outcrops limited to road sections and modern slope failures on hillsides. The type section for this lithofacies is located to the north of Castelbuono, on an escarpment at Cozzo Quattro Finaite (420107 m E; 4203284 m N, Fig. 5f). It comprises grey, thin, laminated siltstones and claystones with rare calcareous mudstones interbedded with thin-bedded micaceous quartz sandstones and quartz siltstones. The sandstone beds range from 1 to 6 cm thick well sorted fine to very fine-grained sand. Some of the beds appear to be ungraded but most are normally graded up to silt. Parallel lamination is common throughout the sandstones and in some cases the lamination is convoluted towards the bed tops. In rare cases, ripples are preserved in the uppermost few centimetres. The bases of thin-bedded sandstone beds are sharp in most of the cases with local very shallow scours (max 1 cm incisional relief) and loading features. Bed tops are invariably sharp. The section also contains some rare sandstone beds up to 12 cm thick. They are normally graded medium to fine grained sandstones, containing parallel lamination that generally passes upward into convolute lamination. The finer grained intervals are represented by light grey laminated siltstones and claystones with beds of 1 cm to up to 1.5 m thick. We interpret this lithofacies as representing deposits from the flanks and from the tails of otherwise bypassing turbidity currents.

4.3.2. *Lithofacies C2 – Slumps*

The type section for this lithofacies is located in a river cut at the base of Pollina hillside (425957 m E; 4203085 m N, Fig. 5g), opposite to Borrelo Basso village. This lithofacies forms cliffs and it is generally associated with medium to thin-bedded sandstones of Lithofacies B4 and C1. Although the type section displays 25 m of continuous slumped section, this lithofacies in general occurs as interbedded with intact intervals of a maximum 1 m thick. It consists of folded and disrupted sandstone bedding (maximum 1 m thick) encased in structureless siltstones. Sand injectites present cross-cutting geometries within the deposit and show irregular thicknesses. We interpret this lithofacies as being the result of local deformation and remobilization of sandstones and siltstones related to intra-basin slope instability.

4.3.3. *Lithofacies C3 – Siltstones*

The type section for this lithofacies crops out at the base of the Pollina outcrop (425816 m E; 4202911 m N, Fig. 5h). However, the unit is generally poorly exposed with sections limited to slope scars on hillsides. This lithofacies is characterized by dark grey thin laminated siltstones. Individual laminae form parallel lamination. Siltstones are rich in mica and organic matter. Very subtle banding within the laminae represents millimetre-scale intercalation with clays. Sorting of the siltstones is good and the beds represent in general ungraded siltstones. Rare, thin beds of 1 cm thick sandstones are interbedded with the siltstones, forming tabular units with sharp bed bases and tops. These sandstone beds are composed of very fine sands and quartz siltites, generally with a high mica content. Bioturbation is rare. We interpret this lithofacies as representing deposits from highly dilute flows – most probably from lateral overflow beyond the main turbidity current conduits that precede the arrival of the main sand-bearing flows into these parts of the basin network. They may also represent amalgamated deposits from the tails of multiple flows on down-system facing slopes.

5. Lateral facies relationships: the Pollina – Castelbuono transect

The Pollina river valley is a natural section through various lithofacies of the Numidian megasequence – providing lateral bed continuity for over 2 km (Fig. 6). The section trends NNE-SSW, approximately perpendicular to palaeoflow. The sequence is gently folded into a broad anticline that plunges towards the NW. Through the section the proportion of sandstone (net to gross) varies, being higher in the north and decreasing southward. These variations are denoted here on logged sections and described, from north to south.

The data presented for Pollina outcrop rely on accurate mapping of the individual bed-sets in the field using the digital application FieldMove. Digital lithological boundaries define the extension and geometry of the bed-traces (Fig. 2a). Faults and structural

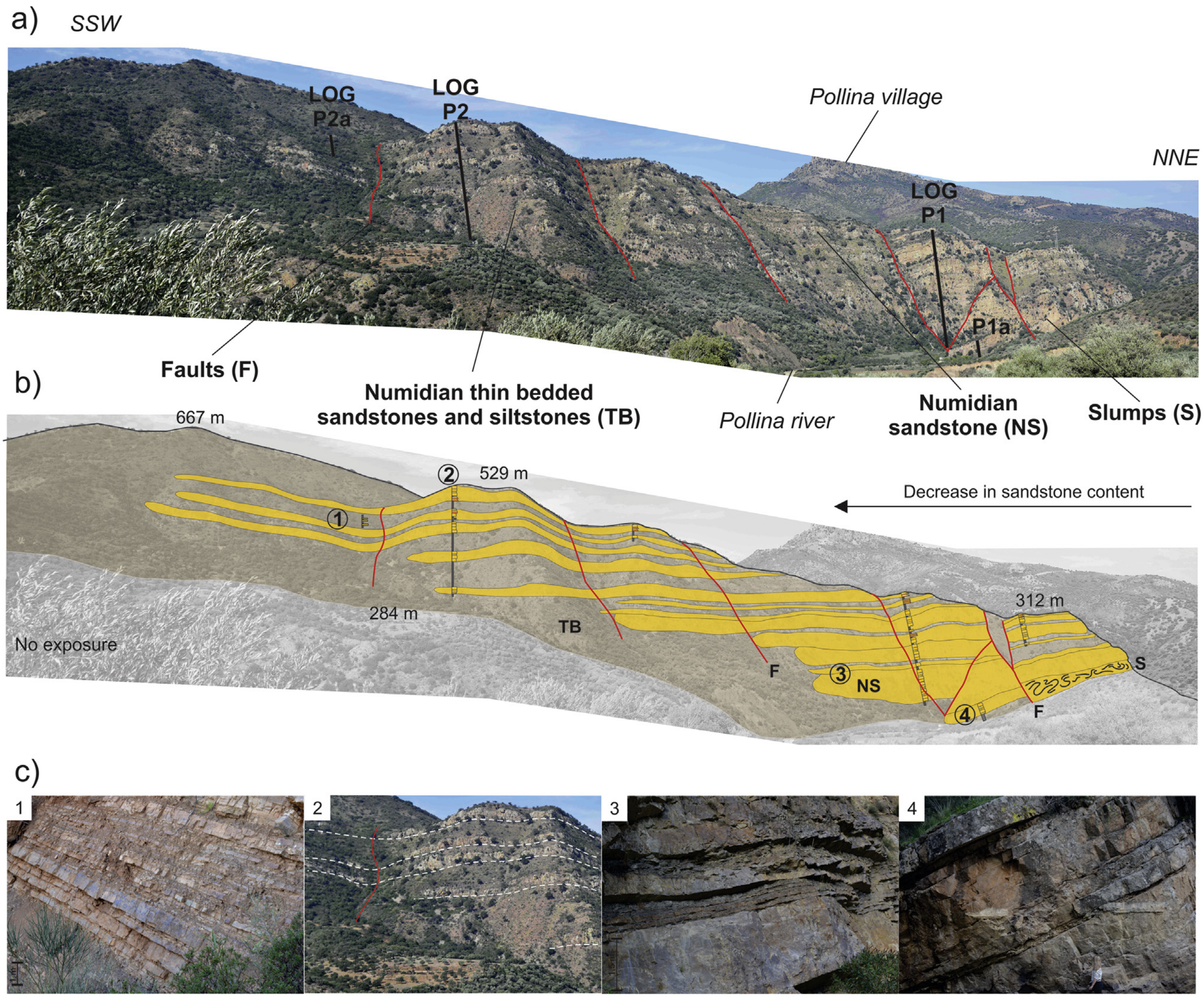


Fig. 6. a) Panoramic view of the Pollina river section, south of Pollina village. Annotations show the sedimentary log locations obtained in this study and indicate examples of the lithofacies outcropping in the section; b) Correlation panel of the Numidian sand bodies according logged stratigraphic sections. They correlate laterally over 2 km and show tabular geometry. Sandstone content decreases towards SSW. The section is perpendicular to the palaeoflow; c) Zoom in photographs to illustrate the type of facies and sandstone bed-set geometry. 1- Thin-bedded sandstones and siltstones are the dominant lithofacies towards the SSW; 2- Detailed photo showing the continuity of the sandstone bed-sets over the fault (dashed lines), which has no major displacement. The photo also demonstrate the pinch-out of the first and second sandstone bed-set towards the SSW, as illustrated in the correlation panel (Fig. 6b); 3- Tabular sandstone bed (1.5 m) interbedded with thin-bedded sandstones and siltstones; 4 – Thick amalgamated sandstone bed-sets are the dominant lithofacies in the northern part of the section.

orientation were carefully considered on defining the bed terminations. The mapping is allied to 6 sedimentary logs of the hillside in scale 1:100, of which 3 are discussed here.

5.1. Northern vertical section

The northern part of the Pollina river section also preserves the deepest stratigraphic levels of this part of the Numidian megasequence. It is illustrated here in a composite log P1 (Fig. 7). This passes through stacked bed-sets that form distinct sand-rich packages separated by thinner-bedded sandstone and siltstone intervals.

The basal 10 m of the northern section, exposed in river cliffs, is sand-poor (Lithofacies C3), comprising dark grey laminated siltstones with rare cm thick fine grained quartz sandstones (Log P1a, Fig. 7a). The lithofacies is capped by quartz sandstones (Lithofacies B2). The contact is sharp, non-erosive and concordant to bedding with both the underlying shales and overlying sandstones.

The sandstone package that overlies the basal contact with the thick siltstone forms a continuous section approximately 20 m thick (log P1a, Fig. 7a). This package consists principally of uniform bed-sets of amalgamated quartz-rich (Fig. 6c-4), medium to coarse sandstone (Lithofacies B2) that are stacked into five bed-sets. These bed-sets appear tabular, extending laterally for at least 500 m into adjacent logged sections. The five main bed-sets are separated by thin (50–60 cm) packages of thin-bedded fine sandstones and siltstones with thin (maximum of 20 cm in thickness) intraformational debrites (Lithofacies B4). Interbedded sandstones and siltstones with associated debrites (Lithofacies C2) are present in some intervals.

The basal sandstone package in Log P1 passes laterally to the NE into a zone of strongly folded and disrupted bedding defined by metre-thick quartz sandstones, encased in debritic siltstones. This slump contains the same lithofacies assemblage as the lower sandstone package. The slumped interval (Lithofacies C2) and its intact continuation in Log P1 is overlain by a package of coarse

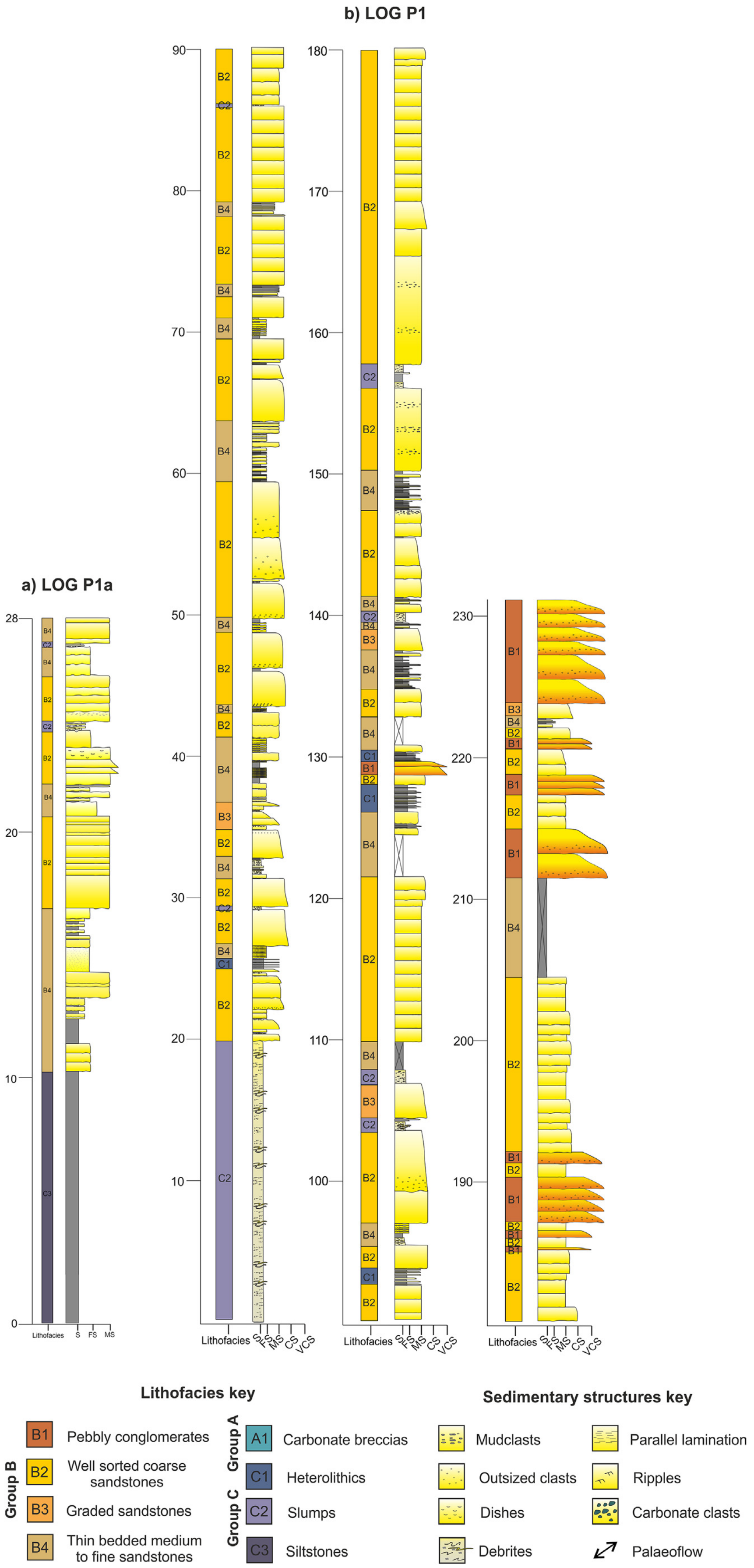


Fig. 7. Composite stratigraphic log P1. a) Log P1a (see location in Fig. 6a) represents the basal section of the northern part of the Pollina river outcrop and show sand-poor deposits (Lithofacies C3), capped by amalgamated Numidian sandstones (Lithofacies B2); b) Log P1 (see location in Fig. 6a) is a full log of the Pollina hillside. It shows a basal slumped interval (Lithofacies C2) overlain by stacked sandstone bed-sets (Lithofacies B2) separated by thin-bedded medium to fine sandstones (Lithofacies B4). The section is coarsening upwards towards pebbly conglomerates (Lithofacies B1) on the very top of the succession. The column at the right-hand side of the log shows the lithofacies type, according to the lithofacies key. Full descriptions are found in Section 4 – Lithofacies of the Numidian megasequence.

sandstones. The basal sandstone bed directly overlies the slumped interval and shows minor compensation across irregularities at the top of the slump.

About 200 m of stratigraphic section, dominantly coarse sandstone, overlies the slumped interval and its intact equivalent form, as shown on the full logged section (Log P1, Fig. 7b). The outcrop divides into five cliff-forming units separated by poorly exposed intervals of less resistant, finer grained strata (Lithofacies B4). Bedsets of amalgamated medium to coarse sandstone (Lithofacies B2) contain individual beds around 1 m in thickness. The thickest bedset towards the top of section contains over 50 individual amalgamated beds. Distinct coarse facies (Lithofacies B1) are found towards the top of the section. The conglomerates form the lower component to beds generally around a metre in thickness that grade up into coarse sandstones. The conglomeratic components form lenticular bodies overlying erosion surfaces that incise (c. 20–30 cm) into underlying sandstone beds. Lenticular conglomeratic units can be traced laterally for about 30 m. In contrast, the coarse sand component in these beds (Lithofacies B2) can be traced laterally into the rest of the bed-set. Graded conglomerate beds stack into packages 5–10 m thick.

A striking feature of the sandstones (Lithofacies B2) that comprise the bed-sets in the NE of the Pollina section (Log P1, Fig. 7b) is the absence of fining-out bed tops. Grain sizes below medium sand are rare within the main bed-sets. The thinner grained intervals that separate the bed-sets are distinct and have abrupt basal contacts onto the underlying coarse to medium sandstones (Fig. 6c-3). This suggests that at this location, although turbidity currents clearly carried a range of grain sizes, for the most part the finer grained fraction was not deposited but bypassed.

5.2. *Lateral variation*

Packages of sandstone with their constituent bed-sets identified in the NE part of the Pollina valley section may be traced SW on the hillside (Fig. 6). Although the upper packages can be followed for over 2 km, the lower ones pinch out laterally (Fig. 6c-2). Overall the stratigraphy becomes finer-grained from NE to SW. This is achieved by an increase in the proportion of thin-bedded sandstones and siltstones (Lithofacies B4) at the expense of bed-sets of amalgamated medium to coarse sandstones (Lithofacies B2). This change is exemplified by comparing Log P1 with an equivalent section, Log P2 1 km to the SW (Fig. 8).

Log P2 contains five packages of medium to coarse sandstones (Lithofacies B2) and, at the top of the log extends into strata that overlie and are marginally younger than those shown in Log P1. Each package on Log P2 consists of a single bed-set of amalgamated sandstone. Conglomeratic lithofacies (Lithofacies B1) occur only towards the top of section. Collectively the sandstone packages vary from 3 to 20 m in thickness but the component amalgamated beds are generally each around 1 m thick. Intervals of finer-grained strata (Lithofacies B4), although poorly exposed, are significantly thicker in Log P2 (Fig. 8a) than in Log P1 (Fig. 7b).

An example of the thin-bedded facies (Lithofacies B4) between the upper two sandstone packages crops out in a track cut towards the top of Log P2. We illustrate this in detail in Log P2a (Fig. 8b). This shows medium to very fine sandstones interbedded with grey laminated siltstones (Fig. 6c-1).

Although the stratigraphic section in log P2 continues up into strata that overlie those recorded in log P1 (see correlation in Fig. 6b), the lower two packages of sandstone in log P2 can be mapped directly into the upper part of log P1. Bed-by-bed correlation between the two logs is not established because of amalgamation within the bed-sets packages. Nevertheless the general bed thickness and number are broadly maintained in the lower two

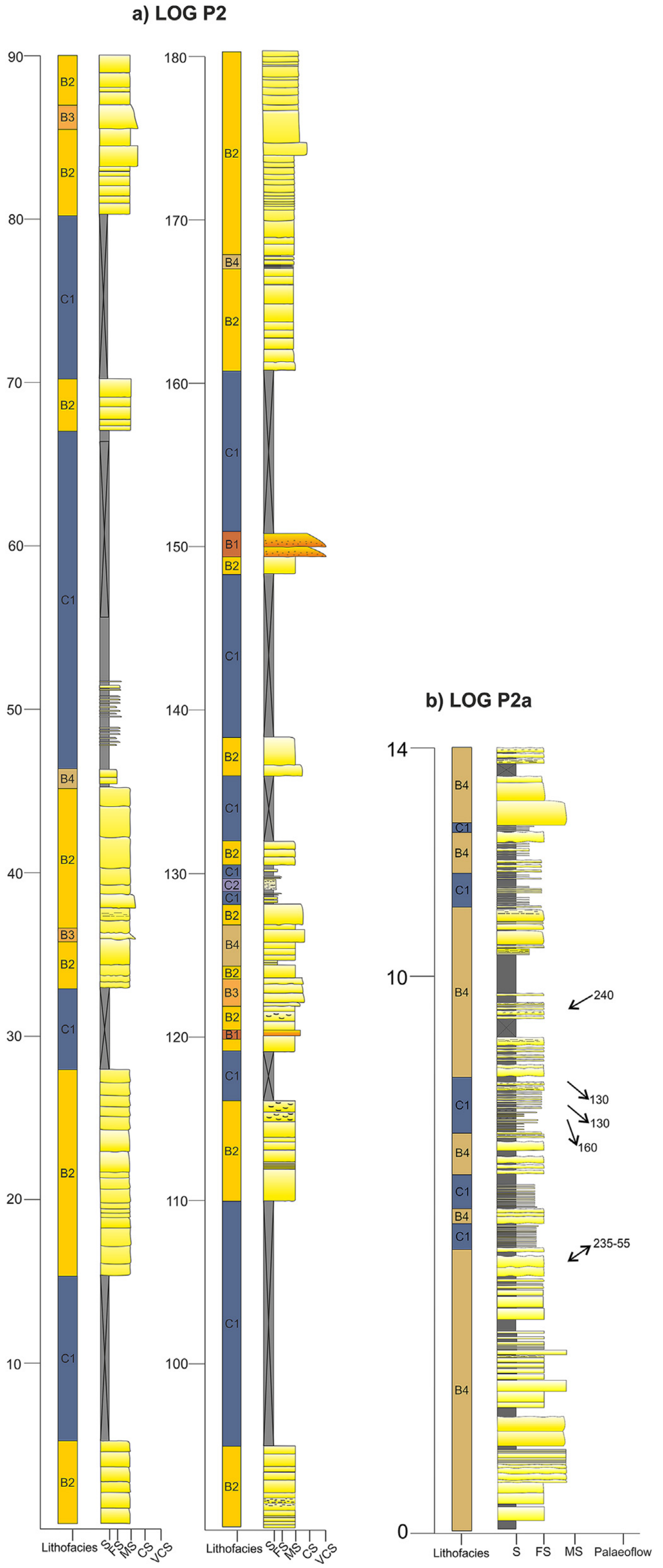


Fig. 8. Stratigraphic log P2 and detailed log P2a. a) Log P2 (see location in Fig. 6a) contains five packages of Numidian sandstones (Lithofacies B2) separated by thick intervals of thin-bedded sandstones (Lithofacies B4); b) Log P2a is a detailed representative log of the thin-bedded sandstone facies (Lithofacies B4) that crops out between the main sandstone packages (Lithofacies B4) and it is usually poorly exposed. Right-hand side column shows lithofacies classification (Lithofacies and sedimentary structures key in Fig. 7).

sandstone packages between logs. However, there are important lithofacies variations. The conglomeratic levels (Lithofacies B1) in the northern log (P1) pass laterally into medium to coarse sandstones (Lithofacies B2) to the south (log P2).

The upper packages of sandstone seen in log P2 can be traced for a further 3–4 km to the SW, broadly retaining not only their composite bed-set 10–20 m thickness, but also the metre-scale thickness of individual beds, their amalgamated character and lithofacies. However, in these SW areas the Numidian megasequence is dominated by siltstone-dominated lithofacies (Lithofacies C1). Unfortunately outcrop is insufficient to establish correlations within the thin sandstone inter-beds beyond the Pollina valley (Fig. 6). Nevertheless we show a representative log (Log P3, Fig. 9) of this finer-grained facies.

Log P3 consists of thin-bedded sandstones (Lithofacies C1) interbedded with intervals of siltstones (Lithofacies C3). Most of the section is dominated of very thin tabular sandstones beds of 1–4 cm thick. They are composed by fine to very fine sands, micaceous quartz arenites and quartz siltstones. In general these beds are normally graded with parallel and ripple lamination. They pass up ubiquitously into siltstone and claystone intervals with composite thicknesses of up to 2 m. The locality also contains rare beds of medium to fine grained sandstone together with thicker beds of medium-grained sandstone (Lithofacies B4). We consider the lithofacies recorded in the log (Log P3, Fig. 9) to be representative of the poorly-exposed area within which it occurs, as it is consistent with the other outcrops and broken slopes. Critically, there is no evidence for coarse sandstones (Lithofacies B2) hereabouts, lithofacies that generally form good outcrops. We infer that these coarser grained, more amalgamated sandstones have pinched out laterally from the exposures in the Pollina river valley.

5.3. *Interpretation: confined Numidian megasequence*

The transect from the Pollina river valley to Castelbuono demonstrates lateral variations in lithofacies over a distance of a few kilometres. The coarse amalgamated sandstones in the north pass gradationally into a siltstone-dominated succession. These variations are oriented laterally to the main palaeoflow recorded in the succession. Therefore we consider the sandstone-dominant northern part of the transect to represent the principal conduit for turbidity currents carrying the coarsest sand fraction. The stacked, amalgamated character of the sandstones suggests repeated transit of turbidity currents over this part of the basin. The southern parts of the transect therefore represent sites that are lateral to the main sand fairway, such that turbidity currents were therefore at least partially confined.

There are two plausible architectures by which turbidites in the Pollina section were confined. One option is through channels. Although the conglomeratic facies, inferred by Thomas and Bodin (2013) to represent the fills of channel axes, display a small amount of incision, there is no evidence of recurrent scouring and coarse lag development along individual surfaces, as is characteristic of morphological channels elsewhere (e.g. Brunt et al., 2007). Rather, each conglomeratic horizon passes up into sandstones that effectively heal the erosional morphology developed on the bed bases. This indicates that the architectural character is constructional. Of course this does not of itself preclude all channel forms – confining geometry could be created through constructional levees. While we cannot eliminate this possibility at Pollina, we consider an alternative more likely: that the causative turbidity currents were confined against structurally-controlled palaeo-slopes.

Lateral facies variations similar to those we describe here from the Pollina-Castelbuono area are described from the Annot system of SE France (e.g. Joseph and Lomas, 2004) and from the Cretaceous of the North Sea (UKCS, Barker et al., 2008). We consider this to be the most plausible explanation – that the Nebrodi basin-floor had structural relief that influenced the routing of the turbidity currents

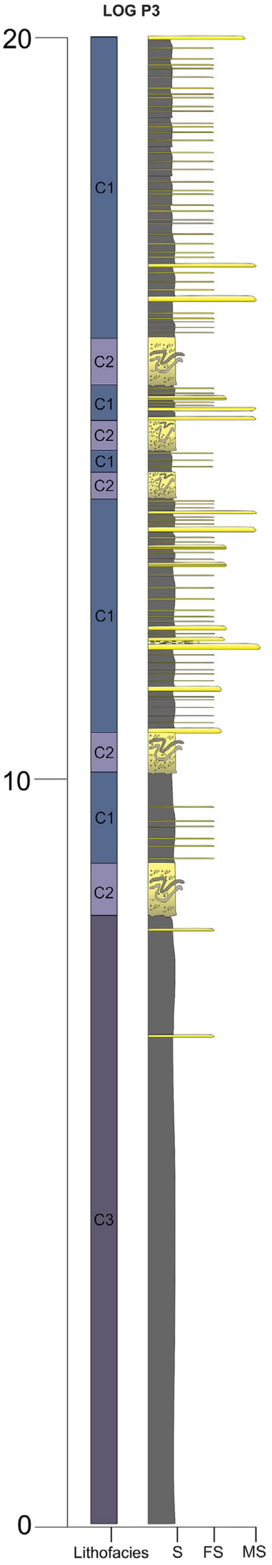


Fig. 9. Stratigraphic log P3. It represents the siltstone-dominated lithofacies (Group C) cropping out along strike to Pollina river section towards SW. Right-hand side column shows lithofacies classification (Lithofacies key and sedimentary structures key in Fig. 7).

that deposited the Numidian megasequence. The northern part of the Pollina section therefore represents a sand fairway developed in the deeper part of the conduit for flows, while the finer-grained facies accumulated on the flanks of the conduit. The pinch-out of the sandstone bed-sets towards the SW defines an onlap surface. Slope confinement decreases upwards in the section and the lateral pinch-out of the subsequent sandstone beds towards the onlap surface moves towards the SW. We will use these interpretations when considering the relationship between the Numidian megasequence and its substrate below.

5.4. Relationships with substrate inliers

Up-dip from the Pollina river section, on hillsides to the east, lie Cretaceous carbonates of the San Mauro Castelverde. Our mapping suggests that the Pollina section directly overlies this inlier, with an unconformity either onto the platform carbonates (as seen at the Portella di Montenero inlier, Fig. 3) or on "Scaglia", as seen in the San Mauro road section (Fig. 4). Confirmation comes from the 2135 m deep Pollina 001 well (ENI-AGIP, 1972). This terminated in intensely fractured fine-grained dolomite, presumably representing the top Cretaceous platform rocks and the local substrate to the Numidian megasequence. The carbonates are overlain by 121 m of dark shales, equivalent to Lithofacies C3. Our outcrop mapping of sandstone bed-sets in the region demonstrates significant topography on the base of the Numidian megasequence with sandstone bed-sets pinching out, presumably through onlap, onto the pre-Numidian substrate or against the basal fine-grained facies (Group C). These relationships are illustrated on two cross-sections through this part of the Nebrodi-Madonie hills (Figs. 10 and 11).

Section A-A' (Fig. 10) runs NW-SE to intersect three inliers of pre-Numidian strata together with the Pollina 001 well. We interpret the variations in substrate elevations that are present in this section to represent normal fault blocks, as previously proposed by Tavarnelli et al. (2001). These control the variations in thickness of Numidian megasequence. The sand-poor lithofacies (Lithofacies C3) lies in lows within this palaeo-bathymetry that is gradually blanketed by sandstones. Thus the Numidian megasequence displays significant thickness variations over a few km. Although previous maps (Servizio Geologico D'Italia, 2012) show carbonate breccias cropping out near to Portella di Montenero quarry, the Numidian megasequence does not record evidence of an active substrate (e.g. rotation, divergent strata) during sedimentation in this area.

Section B-B' (Fig. 11) runs NE-SW and illustrates the lateral variation in the proportion of lithofacies established in the Pollina river valley. The section runs onto the flank of the main substrate outcrop on the Madonie Mountains. Thick amalgamated sandstone units, characteristic of the northern Pollina section, are not evident approaching the substrate. Instead the Numidian megasequence adjacent to the substrate is dominated by shales and thin-bedded sandstone beds (Lithofacies C1 and C3). As section B-B' is perpendicular to regional palaeoflow recorded by the turbidites. There are significant lateral variations in deposit character. We presume that within this transect it is the thick sandstone-rich sections that represent the main dispersal path for the turbidity currents from which they deposited. The finer grained facies were therefore deposited on the edges of these flows, presumably on a syn-depositional slope that dipped gently N to NE (in the modern orientation). This palaeo-slope presumably provided at least local, structural confinement to the turbidity currents. Unfortunately, field relationships do not allow us at present to establish whether this regional slope was structurally active during deposition or simply inherited.

6. Madonie section

The hillsides on the SE edge of the Madonie Mountains, the eastern slope of Monte San Salvatore (1912 m) opposite to the town of Petralia Sottana (Fig. 2a), contain key localities for establishing the relationship between the Numidian megasequence, its constituent lithofacies and its substrate. Lentini and Vezzani (1974) and others infer that these outcrops lie on the souther limb of an anticline. This is cored by extensive outcrops of dominantly Cretaceous platform carbonates that have been carried southwards (in present orientation) on a thrust during the development of the Maghrebian orogenic wedge (Fig. 2c). The thrust displays composite history, with its most recent phase of activity of early Pliocene age. However, it juxtaposes distinct tracts of pre-Numidian substrate during earlier periods in its history. Our focus here is on its early history – our contention being that it controlled Numidian deposition at this location. The area is therefore especially important because it challenges many current interpretations of the Numidian megasequence as being deposited on a broadly unconfined basin-floor in an unstructured orogenic foredeep (c.f. Guerrera et al., 2012). We have mapped part of the slopes of Monte San Salvatore (Fig. 12) that constitute a NE-SW orientated kilometre-scale profile through the forelimb of the thrust anticline.

Although bed-sets can be readily traced in high resolution ortho-photographs across the hillsides of Monte San Salvatore, individual layers of carbonate breccia were tracked directly in the field by walking out their traces. These bed-traces, together with their measured structural orientations, were recorded digitally via Field Move software onto a base map. Notebook sketches and photographs were used to record the carbonate breccias geometries in cross section view. It is this precision that permits recognition of lateral variations in structure and facies.

The SW Madonie area includes our type area for the platform-derived carbonate breccias that comprise lithofacies A1 (Figs. 5a and 12c-3). Cliff-forming bed-sets of these breccias are interbedded with heterolithics (Lithofacies C1) (Fig. 12c-2). These thin beds are characterized by 1–5 cm thick tabular fine-to very fine

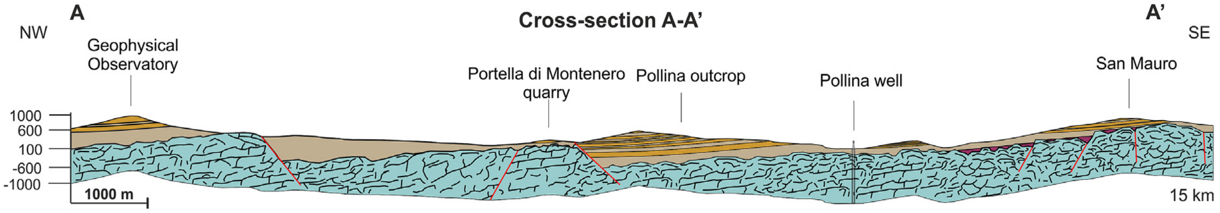


Fig. 10. Cross section A-A' (see location in Fig. 2a). The section shows limestones (Numidian substrate) structured by normal faults. These structures are interpreted to have controlled the variations in thickness and facies of the Numidian megasequence. The main localities shown in this cross section were previously described above: Portella di Montenero quarry (Fig. 3), San Mauro (Fig. 4) and Pollina outcrop (Fig. 6).

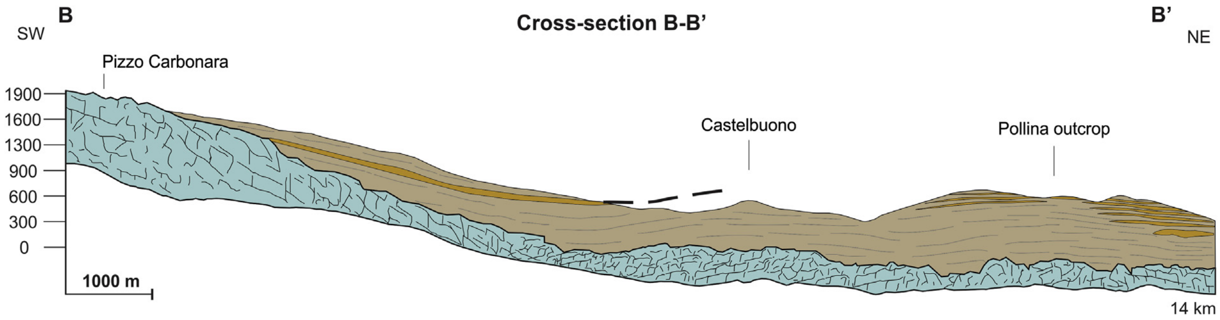


Fig. 11. Cross section B-B' (see location in Fig. 2a). The section illustrates the lateral facies variation in the proportion of lithofacies established in the Pollina river valley. The sand-rich lithofacies (Lithofacies B2) are deposited in the northern side of the section, represented by the main sand-fairway; while the finer-grained facies (Lithofacies B4) are deposited on the edges of the sand-fairway. This abrupt lithofacies variation is related to the structural confinement of the turbidity currents by the palaeo-slope created by structures in the substrate.

grained quartz sandstones interbedded with laminated grey siltstones (Fig. 12c-4). Our mapping of the individual elements within this succession of breccia units and the siltstone-dominated fine-grained turbidite facies reveals lateral and vertical changes across the outcrop. Breccia bed-sets are more frequent in the NE of the outcrop and gradually decrease in abundance and become more regularly spaced towards the SW where they eventually pinch-out completely (Fig. 12c-2). The average carbonate clast size within the breccias also decreases towards the SW. Larger carbonate blocks are concentrated to the NE adjacent to the substrate exposure. The carbonate breccias display a subtle gradual angular dip variation up section. Older bed-sets of breccias have higher dip angles than the younger strata. The thin-bedded turbidites show weakly-discordant relationships with the carbonate breccias, each apparently onlapping their underlying breccia bed-set (Fig. 12d).

The succession of interbedded thin-bedded turbidites and carbonate breccias has been termed the Argille di Portella di Mandarini Formation by some workers (Grasso et al., 1978; Lentini and Vezzani, 1974). Collectively these two lithofacies represent a palaeo-slope facies association. The carbonate breccias represent rock-falls from high on the palaeo-slope with the heterolithic facies representing the deposits of turbidity currents that skirted the base of the slope. This slope faced broadly southwards (in present orientation) during deposition, which is the same general direction as the larger-scale forelimb of the structure that folds the limestones substrate.

The southern part of the Monte San Salvatore hillside (directly under the chapel of Madonie dell' Alto, Fig. 12a) contains a succession of quartz sandstones, chiefly of Lithofacies B2 (Log M1, Fig. 13). Flute casts (although rarely preserved due to amalgamation), indicate flow towards the SE at the base of the section, changing to E upwards in the section (in present orientation).

The sandstone cliff of Monte San Salvatore (Log M1, Fig. 13) overlies the succession of heterolithic facies (Lithofacies C1) and carbonate breccias (Lithofacies A1). The contact between the underlying fine-grained deposits and the sandstones is shallowly erosive (c. 10 cm). The sandstone package forms a continuous section 229 m thick composed of uniform bed-sets of amalgamated, medium to coarse quartz sandstone (Lithofacies B2) (Fig. 12c-1) stacked into eight bed-sets. These bed-sets appear tabular laterally, for at least 1 km, where individual sandstones beds begin to thin out gradually towards the sequence of heterolithics and carbonate breccias. The eight main bed-sets are separated by poorly exposed intervals of less resistant, finer grained strata (Lithofacies B4). Bed-sets of amalgamated very coarse to medium sandstones (Lithofacies B2) contain individual beds ranging from 20 cm to up to 2 m thick. The thickest bed-set found towards the top of the section contains over 40 individual amalgamated beds. Pebbly conglomerates (Lithofacies B1) are present in the middle part of the section. The conglomerates form the basal component of beds about 1 m thick that grade upwards into coarse sandstones. The basal contact into the underlying sandstones is weakly incised (c. 20 cm), forming lenticular bodies. These graded conglomerate beds stack into packages of up to 7 m thick. The packages of conglomerates are overlain by bed-sets of amalgamated sandstones that form the remainder of the section. The finer grained intervals that define the limits between the sandstone bed-sets are represented by intervals of siltstones and thin-bedded sandstones (Lithofacies B4) of about 5 cm thick. Well-exposed intervals of this lithofacies show debritic siltstones and slightly folded thin-bedded sandstones. They show distinct and abrupt bases onto the underlying coarse to medium sandstones, representing bypassing of the most of the finer grained fraction of the flows.

One level within the cliff section of amalgamated sandstone contains scours filled with rounded carbonate clasts up to 10 cm across, within a matrix of coarse sandstone (Fig. 14). We interpret these to represent lags. This is a critical observation for it ties the palaeo-slope from which the carbonate breccias were derived to the deposition of sandstones, presumably along the base of the palaeo-slope.

The facies relationships described above are illustrated on a schematic cross section (Fig. 15) showing lateral variations in the Numidian megasequence over a few km. The carbonate breccias beds indicate active tilting of the slope during Numidian deposition; a deduction supported by the repeated occurrence of breccias, which record recurrent slope failure. As the palaeo-slope lies on the flank of the anticline, that forms the southern flank of the carbonate platform of the Madonie Mountains, it strongly suggests that the Numidian megasequence was deposited during active thrusting in the substrate. This palaeo-slope would have provided local structural confinement to the turbidity currents from which both the main sandstone (Lithofacies B2) and thin-bedded sandstones and siltstones (Lithofacies C1) were deposited.

7. Discussion

7.1. Comparison with existing lithofacies schemes

The field relationships presented here challenge many existing lithofacies and tectonostratigraphic schemes for the Numidian megasequence on Sicily (Bello et al., 2000; Catalano and D' Argenio, 1982; Guerrera et al., 2012, 2005, 1992; Thomas et al., 2010) and beyond (Belayouni et al., 2013, 2012; D'Errico et al., 2014; Patacca et al., 1992; Sami et al., 2010), as well as challenging established

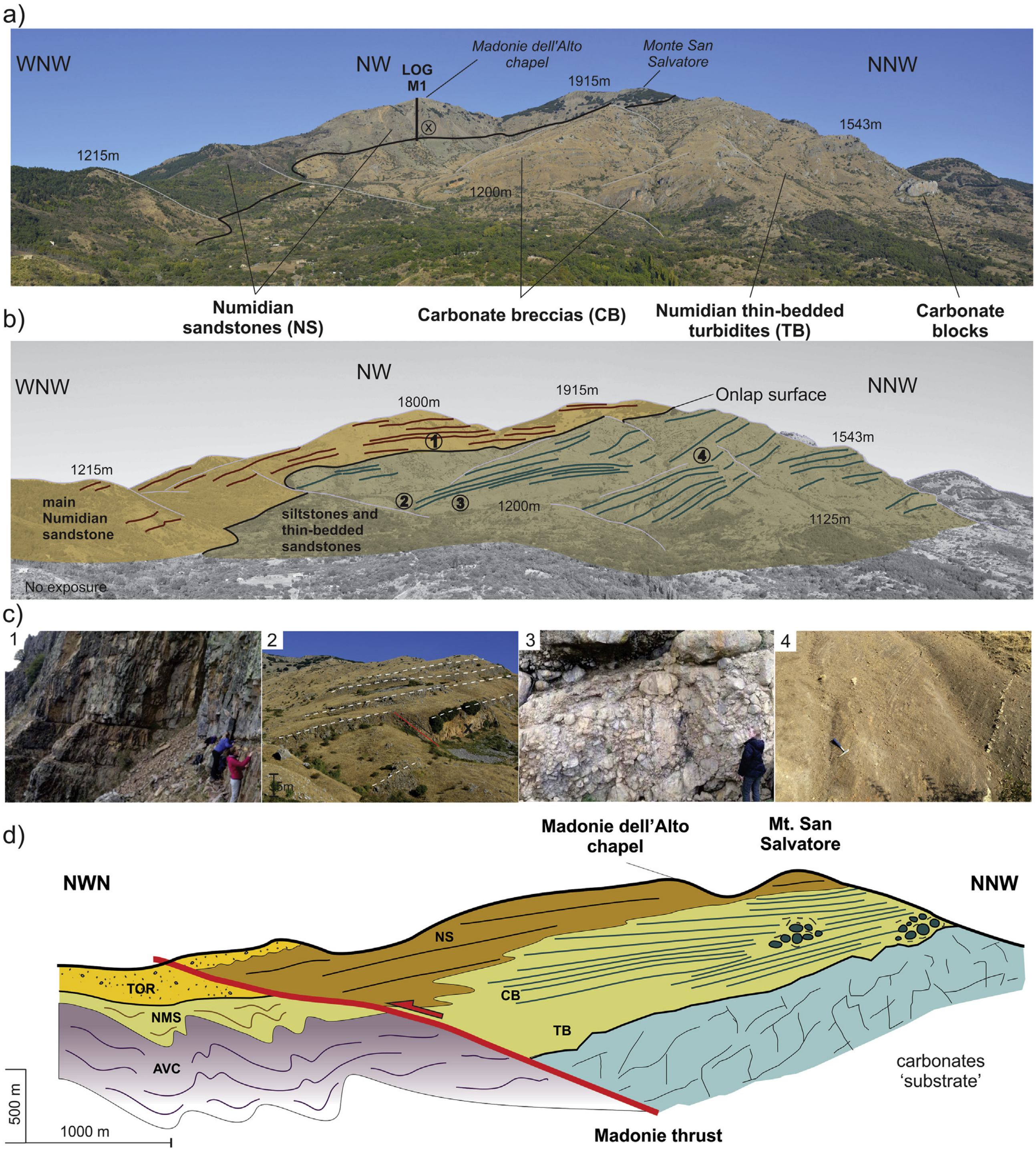


Fig. 12. a) Panoramic view of the Madonie section, SE edge of the Madonie Mountains. Annotations show the sedimentary log location obtained in this study and indicate examples of the lithofacies outcropping in the section; b) Correlation panel of the carbonate breccias (Lithofacies A1), interbedded with Numidian thin-bedded turbidites (Lithofacies C1). Carbonate breccias gradually decrease in abundance and become more regularly spaced towards SW. They also show a subtle up-section gradual angular variation, a characteristic of syn-kinematic strata. A thick Numidian sandstone section overlies the succession of thin-bedded turbidites and carbonate breccias in the southern part of the Madonie section. The sandstone thickness decreases towards NE and defines an onlap surface. The section is perpendicular to the palaeoflow; c) Zoom in photographs to illustrate the type of facies and geometry. 1- Thick succession of amalgamated sandstone bed-sets of Numidian showing tabular geometry; 2- Photo showing the lateral continuity of the carbonate breccias beds (dashed lines) and their pinch-out towards the SW, as illustrated in the correlation panel (Fig. 12b); 3- Detailed photo of the carbonate breccias. The bed-sets measure up to 10 m in thickness, and consist of poorly sorted limestones and dolostones clasts sourced from the underlying substrate. Location of the photo marked with (x) in Fig. 12a; 4 – Example of the thin-bedded sandstones and siltstones which are interbedded with the carbonate breccias; d) Cross section through the S margin of the Madonie showing the relationship of the fold limb beneath Monte San Salvatore and the underlying thrust. Note that this structures displays a composite history.

structural interpretations for northern Sicily (Bianchi et al., 1987; Broquet, 1972; Servizio Geologico D'Italia, 2012).

The main sandstone lithofacies described here (Lithofacies B1–B3) is conventionally termed the Geraci Siculo Member (e.g. Accordi, 1958; Carbone and Grasso, 2012). The other lithofacies (Group A, Lithofacies B4 and Group C) comprise two distinct tectonic units termed Pizzo Dipilo-Pizzo Carbonara and Monte San Salvatore (Carbone and Grasso, 2012). As discussed, the association of carbonate breccias (Lithofacies A1) and the interbedded heterolithics (Lithofacies C1) are generally grouped into the Argille di Portella di Mandarini Formation (Grasso et al., 1978; Lentini and Vezzani, 1974), otherwise termed the Portella Colla Member (e.g. Ogniben, 1960). In regional studies of the Numidian (Guerrera et al., 2012, 2005) these different units are correlated over long distances but at individual location areas are considered to be deposited at distinctly different times. In the Nebrodi-Madonie hills, our study area, the Argille di Portella di Mandarini, the Geraci Siculo Member and the lithofacies grouped in the two tectonic units are considered to be different ages. Our research shows these distinctions to be false. The different lithofacies are coeval over short distances of a few km and reflect different positions relative to the main routing pathways for the turbidity currents that deposited them. Such short-range variations are characteristic of confined turbidite systems. Presumably the pre-existing assumption that the different lithofacies groups in the Nebrodi-Madonie Mountains have distinct stratigraphic ages arises from the adoption of unconfined fan models. Here we propose that the facies associated described above record distinct and local structural influences on the deposition of the Numidian megasequence.

7.2. *The structure of northern Sicily*

The new kilometre-scale lithostratigraphic correlations presented here challenge existing structural models for the Nebrodi-Madonie area. Although the original geological mapping (Lentini and Vezzani, 1974) showed continuity of sandstone bed-sets, a pattern confined and extended by our mapping, more recent studies have incorporated imbricate thrusts to account for the lateral variations in lithofacies. These imbricate structures are incorporated in regional cross-sections throughout northern Sicily (e.g. Bianchi et al., 1987). We consider these more complex structural configurations to be unwarranted and indeed falsified by the bed-set patterns at outcrop. The Nebrodi-Madonie hills are better interpreted as a broadly continuous basin, uplifted along with its Mesozoic substrate during and following deposition through the Miocene. In this sense the Numidian megasequence was deposited upon an active substrate.

7.3. *Implications for the Numidian system*

The observations made here indicate that the substrate to the Numidian is not a reliable guide to restore the position of strata within the Maghrebian chain. Cross-sections and stratigraphic correlations through Sicily and elsewhere that use this approach (Bianchi et al., 1987; Broquet, 1970; Catalano et al., 2013), and their implications for large-scale tectonic evolution and palaeogeography will need re-evaluating. Likewise, interpretations of the Numidian system itself, both within northern Sicily and by implication throughout southern Italy, that consider it as the fill to an unstructured foredeep basin (Giunta, 1985; Grasso, 2001; Guerrera and Martín Martín, 2014; Guerrera et al., 2012; Wezel, 1970) are false. In regional studies this has carried the implication that thrust structures entirely post-date Numidian strata. The field relationships described here for the Nebrodi-Madonie render such

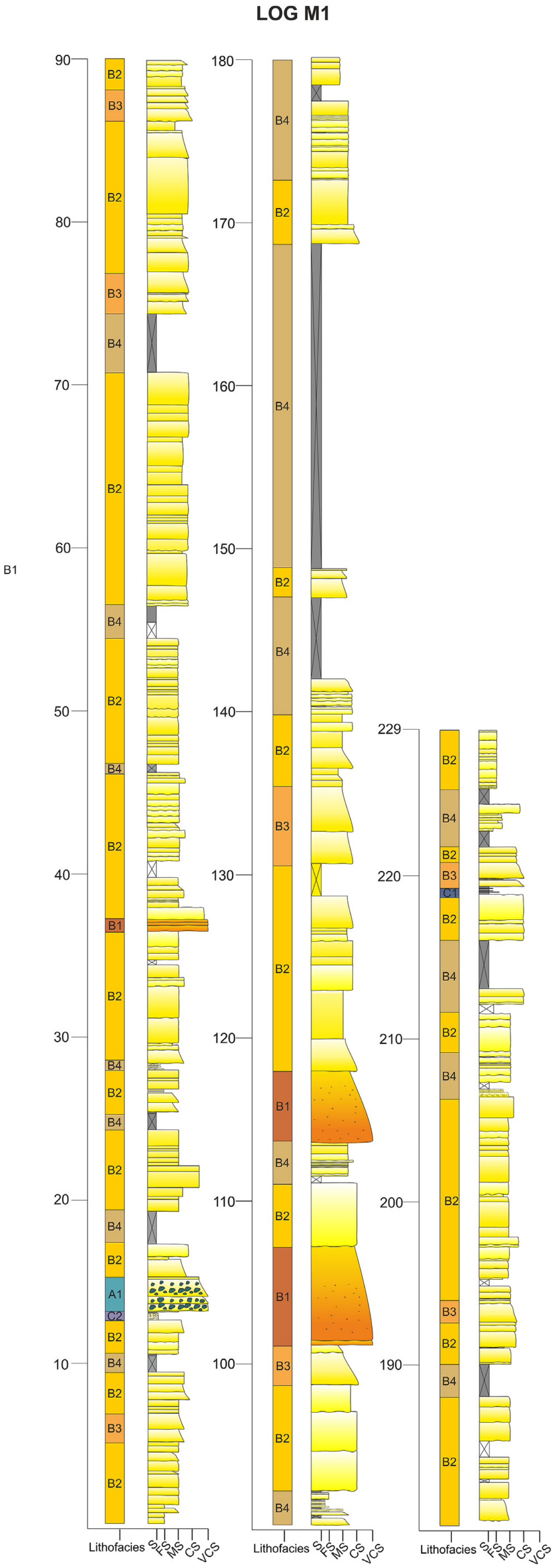


Fig. 13. Stratigraphic log M1 (see location in Fig. 12a). Log M1 contains eight packages of Numidian sandstone (Lithofacies B2) separated by intervals of thin-bedded sandstones (Lithofacies B4). Coarser facies (Lithofacies B1) crop out in the middle of the section. Right-hand side column shows lithofacies classification (Lithofacies and sedimentary structures key in Fig. 7).

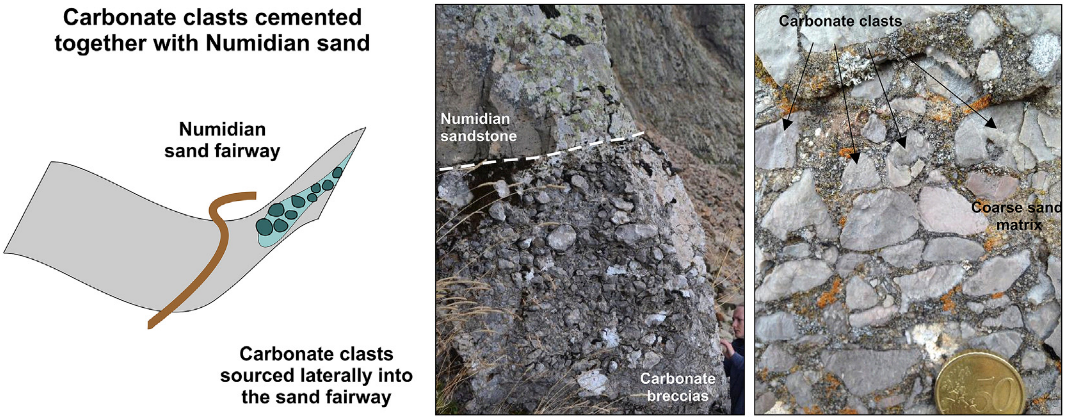


Fig. 14. Lags of carbonate clasts cemented together with Numidian coarse sandstone. The clasts are sourced from the active palaeo-slope, laterally to the main Numidian sand-fairway. This outcrop is recorded at the base of log M1 and its location is annotated as (x) in Fig. 12a.

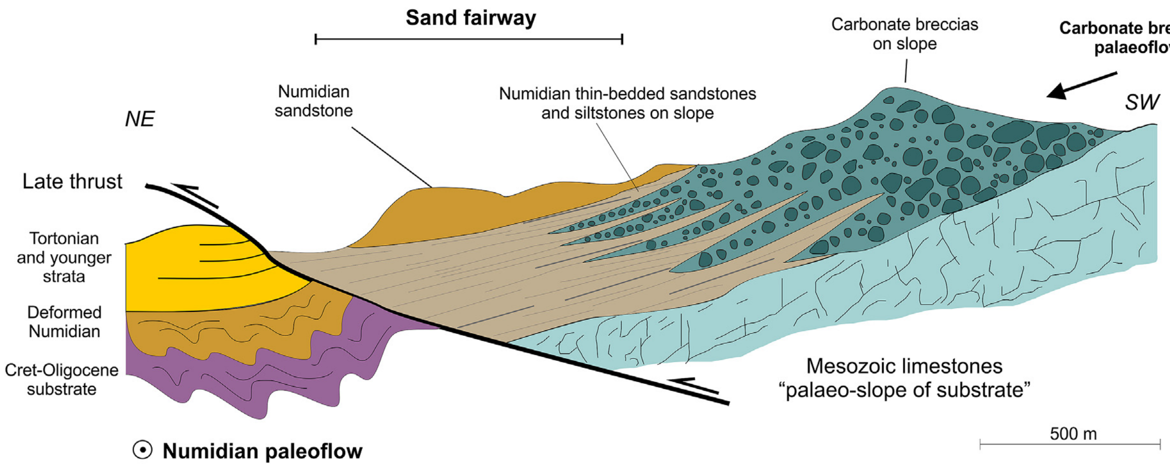


Fig. 15. Schematic cross section of the Madonie area showing the short lateral facies variations related to the local structural confinement of the turbidity currents. The palaeo-slope (formed by tilted and folded carbonates) confine the turbidity currents into a main sand fairway. The interaction between the palaeo-slope and the Numidian sand fairway is recorded by the recurrent deposition of carbonate breccias interbedded with thin-bedded lithofacies. The carbonate breccias indicate active tilting of the slope during Numidian deposition. A later thrust disrupts the base of the section.

simple inferences unsound. There is no simple distinction between a foredeep and thrust-top megasequence – deposition can spill between both structural settings. There are several modern-day analogues for this type of submarine sediment routing, such as offshore Taiwan (Hsiung and Yu, 2013; Hsiung et al., 2015) and Brunei (Morley and Leong, 2008; Morley, 2009). These modern localities show that depositional systems can pass from thrust-top to foredeep (and vice versa) one into the other, behaviors that are presumably more likely for axially-delivered turbidity currents (Fig. 16).

For axially delivered turbidites, basin-floor structures can act as sediment pathways but also interact with the turbidity currents creating ponding, deflection and reflection of the flows (Sinclair and Tomasso, 2002). These processes are responsible for the short-range facies variations within the turbidite basin. Short-range facies variations have been documented in other confined turbidite systems such as Annot (Salles et al., 2014) and Marnoso Arenacea (Tinterri and Tagliaferri, 2015). We consider the deposition of Numidian turbidites to have taken place over a complex structured substrate (Fig. 16). Like other confined turbidite systems, the sand fairway is routed by basin-floor structures. The structural confinement of the turbidity currents exert major control in the sand distribution and associated facies variations. As shown here, sand-rich fairways can pass laterally into significantly siltier successions over a few hundred metres. Clearly if these relationships are appropriate outcrop analogues for structurally confined turbidite systems in general, the Numidian of northern Sicily offers excellent illustrations of the risks of predicting reservoir distributions in modern subsurface settings.

8. Conclusions

Although some existing studies suggest protracted deposition, it seems probable that the Numidian megasequence of northern Sicily accumulated during a short (1–3 million year) period in the Burdigalian. It was deposited within basins that had been restructured after the Mesozoic such that Jurassic-Cretaceous tectonostratigraphic units (Panormide) had little relevance for the Miocene palaeogeography. The Numidian shows short range (km) facies variations that are consistent with its behaviour as a partly confined turbidite system. Its causative turbidity currents interacted with both basin floor and flank topography. In places this topography was related to structures inherited from the tectonic activity that reconfigured the Mesozoic platform palaeogeography but were inactive during Numidian deposition. However, at least locally, Numidian deposition occurred adjacent to and across active thrust

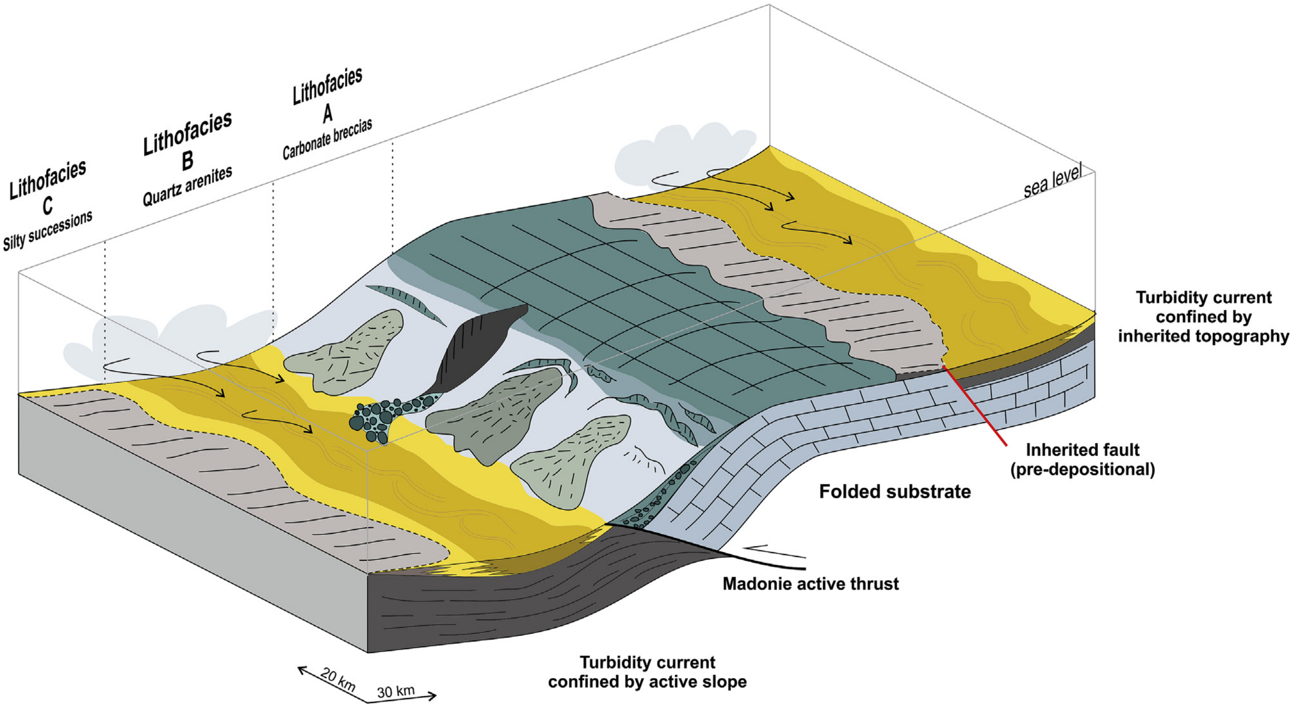


Fig. 16. Block diagram illustrating how facies variations relate to substrate structure on either side of the Madonie inlier.

structures, which presumably formed part of the fledgling Maghrebian orogen. The Numidian of northern Sicily, hitherto interpreted as highly disrupted and dismembered by subsequent thrust structures, is actually reasonably intact with little evidence for major map-scale thrusts. Not only does this interpretation provide an improved framework for understanding depositional architectures and facies variations within the Numidian turbidite system, it also challenges existing structural interpretations of northern Sicily. Our deduction that the Numidian of the Nebrodi-Madonie area was deposited across growing thrust systems and behaved as a structurally-confined system also challenges existing regional understanding of this system. It remains to be seen how this new tectonostratigraphic model can be applied to other parts of the Numidian system, on Sicily and beyond. Regardless of these future research directions, the Numidian of northern Sicily provides an excellent analogue that may inform further investigations in similar tectono-stratigraphic settings, where mature craton-derived quartz sands are flushed into tectonically active marine basins.

Acknowledgements

The research presented here is funded by BG Group in partnership with CNPq-Brazil (National Council for Scientific and Technological Development). Rosanna Maniscalco acknowledges a FIR 2014 grant awarded by the University of Catania, Sicily. Patricia Pinter thanks Prof. Karin Goldberg for helpful discussions in the field and Thisiane dos Santos, Francesca Porro and Dario La Camiola for extensive field assistance. Finally we thank Simon Lomas and the anonymous reviewers for their constructive comments that helped us to improve this paper.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.marpetgeo.2016.09.014.

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