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# Tracking sand-fairways through a deformed turbidite system: the Numidian (Miocene) of Central Sicily, Italy

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## ABSTRACT

Understanding ancient deep-water sedimentary systems that accumulated at complex plate boundaries requires confronting the stratigraphic record of deformed sedimentary successions by tracking sand-fairways and identifying original relationships in later deformed sequences. Here, we investigate the Numidian turbidite system (early to mid-Miocene) of Central-East Sicily to explore a deep-water sedimentary system deposited at an active thrust belt on the Central Mediterranean. Turbidites include multi-metre thick-bedded, ultra-mature quartz sandstones that were sourced from North Africa and are now deformed and dismembered within the Apennine-Maghrebian orogen. To date, much research has focused on the little-deformed sections that sample discrete parts of the original turbidite pathways. Yet the bulk of these systems are represented by deformed successions and these have attracted little modern sedimentological and stratigraphic investigation. We present new data based on field mapping, sedimentological/structural fieldwork, and biostratigraphy (planktonic foraminifera and nannofossils) that focus on the Numidian turbidites of Central-East Sicily. Thickness and facies variations, together with evidence of large-scale sediment bypass and local substrate reworking, characterize the Numidian turbidites of the study area, consistent with a partially confined turbidite system. Our work demonstrates that the Numidian turbidite system accumulated across active structures and these provided tortuous, evolving corridors through which turbidity currents were routed, transporting coarse sand over many hundreds of km. These results provide insight on structurally confined turbidites in analogous tectonic settings and demonstrate the need to seek sedimentological and stratigraphic data from deformed and dismembered parts of deep-water systems.

## INTRODUCTION

Craton-derived deep-marine sandstones provide important hydrocarbon reservoirs in several complex plate boundary systems, such as the Southern Caribbean (Deville *et al.*, 2015). However, tracking sediment dispersal patterns in tectonically complex settings is difficult, especially when the timing and distribution of substrate deformation is not well-constrained. A challenge lies in understanding sediment routing through tectonically active basins and its impact on facies variations in sedimentary successions that were subject to progressive post-depositional deformation. Post-depositional deformation can compromise spatial and stratigraphic relationships (e.g. geometries, outcrop continuity and facies variations), however the comprehension of large-scale depositional systems requires that these more deformed segments be understood alongside the less-deformed ones. In complex basins, where undeformed or only partially deformed sections are rare, less preserved sites are important to determine the influence of a deforming substrate on the turbidity current deposition as well as providing information on facies, thickness variations and depositional style. We explore these issues using the Miocene Numidian system on Sicily.

System-scale studies in turbidite basins can inform understanding of tectonic evolution (e.g. Sinclair & Tomasso, 2002; Salles *et al.*, 2014), especially where sedimentation is controlled by developing structures. Basin-floor structures control turbidity current deposition and play an important role determining accessibility of sediment supply in various parts of the basin. Sediment

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distribution variations in confined turbidite systems such as Marnoso Arenacea of the Northern Apennines of Italy (e.g. Tinterri & Tagliaferri, 2015) have been attributed to shifting of sand-fairways against basin-floor structures. In general, the interaction of sand-fairways with basin-floor structures creates zones of deposition, erosion or bypass which are recorded by the basin stratigraphy and sedimentology (e.g. Kneller, 1995; McCaffrey & Kneller, 2004). Some sedimentological features (e.g. amalgamated, thick sandstones with abrupt tops, mud caps, and palaeoflow reflection/deflection) are considered to be indicators of this interaction and are widely described for confined systems such the Annot turbidites (SE France; e.g. Joseph & Lomas, 2004) and the Tres Pasos Formation (Chile; e.g. Stevenson *et al.*, 2015). Collectively, the basin stratigraphy and sedimentology allow us to track the sand-fairways and deduce the substrate configuration upon which the turbidity currents were deposited.

Here, we accept the challenge of reconstructing the substrate configuration of part of the Numidian turbidite system (Miocene) in the Central Mediterranean by tracking sand-fairways, which are now outcropping as deformed segments. The work builds upon our previous work in apparently less-deformed parts of the system in Northern Sicily (Pinter *et al.*, 2016) but focuses on outcrops ca. 50 km further down-system, in Central-East Sicily (Fig. 1). Our aim here is to test whether a general model for Numidian deposition as a turbidite system confined by active substrate is more widely justified. This requires using evidence from deformed sites to infer sediment routing and its evolution through time. We integrate sedimentological/structural fieldwork and biostratigraphical data (planktonic foraminifera and calcareous nannofossils) from three main sites of Central-East Sicily – Mt. Salici/Gagliano, Sperlinga and Pietra Perciata (Fig. 2a) – to propose a new tectono-stratigraphic model for the Numidian megasequence of Sicily. We first establish the age of the successions using new biostratigraphic data. We then describe thickness variations and assess the sedimentology of the Numidian turbidites to identify zones of sediment accumulation, erosion and bypass. Collectively, these data will allow us to infer presence and progressive development of basin-floor structures and their impact on sediment routing. We are confident that this study will not only establish the Numidian as an analogue for turbidites in equivalent tectonic settings, but it will also promote wider understanding of the Mediterranean palaeogeography.

## NUMIDIAN OF THE SICILIAN STUDY AREA

Ogniben (1960) recognized that the Numidian as Oligo-Miocene deep-water sandstones of the Numidian system on Sicily were derived from the North-African craton and shed into the dynamically evolving Maghrebian orogenic system. This orogenic system developed as a result of the convergence between the European and Africa-Adria plates during the Late Cretaceous to Pleistocene (Elter *et al.*, 2003). Our study focuses on that part of the Numidian system that was deposited in the Central Mediterranean and is now preserved in thrust-sheets on Sicily and in the Southern Apennines. Due to the progressive deformation of the Maghrebian orogenic system, the outcrops in Sicily have experienced a ca. 100° clockwise rotation since deposition while those in the Southern Apennines have experienced a similar anti-clockwise rotation (Speranza *et al.*, 2003; Fig. 1).

As with many turbidite systems deposited in tectonically active basins, the evolution of the Numidian system is still a matter of debate. Existing system-scale understanding (e.g. Guerrera *et al.*, 2005 and references therein) suggests that the Numidian was deposited across an unstructured marine basin and the current configuration is entirely the result of post-depositional dismembering such that original stratigraphic relationships cannot be determined. This assumed depositional setting has underpinned a lithostratigraphic scheme that assumes that spatially distinct facies correspond to temporally/spatially distinct parts of the basin (Bianchi *et al.*, 1987; Lentini *et al.*, 1991; Guerrera *et al.*, 2012). This orthodoxy is challenged by Pinter *et al.* (2016) who show that, in northern Sicily (Nebrodi-Madonie area; Fig. 1), the Numidian accumulated across an actively thrusting substrate displaying characteristics of a strongly confined depositional system. Thus, the various lithostratigraphic units of previous workers (Carbone *et al.*, 1990; Lentini *et al.*, 1991; Renda *et al.*, 1999; Guerrera *et al.*, 2005, 2012 are short-range lateral equivalents of one another – with facies changes over 5–10 km associated with basin-floor topography. Therefore, we group all these facies into a single Numidian megasequence, in the sense of Hubbard *et al.* (1985) and Williams (1993). Note that we have refrained here from using conventional architectural terms such as lobe and fan for these imply down-system expansion of the depositional unit and are thus potentially misleading for deposition in narrow, structurally restricted corridors (e.g. Southern *et al.*, 2015). Here, we apply this new understanding to parts of the Sicilian sector that have been more extensively deformed by syn-and-post-Numidian thrusting and are now deformed, dismembered, eroded and buried beneath younger strata (Fig. 2b).

The Numidian of Central-East Sicily lies stratigraphically upon Cretaceous-Oligocene deep-water mudstones termed the *Argille Varicolori* (Catalano *et al.*, 1974; Grasso *et al.*, 1978), with a distinctive level of carbonate turbidites, up to ca. 50 m thick, termed the *Polizzi Formation* (Carbone *et al.*, 1990; Fig. 2c).

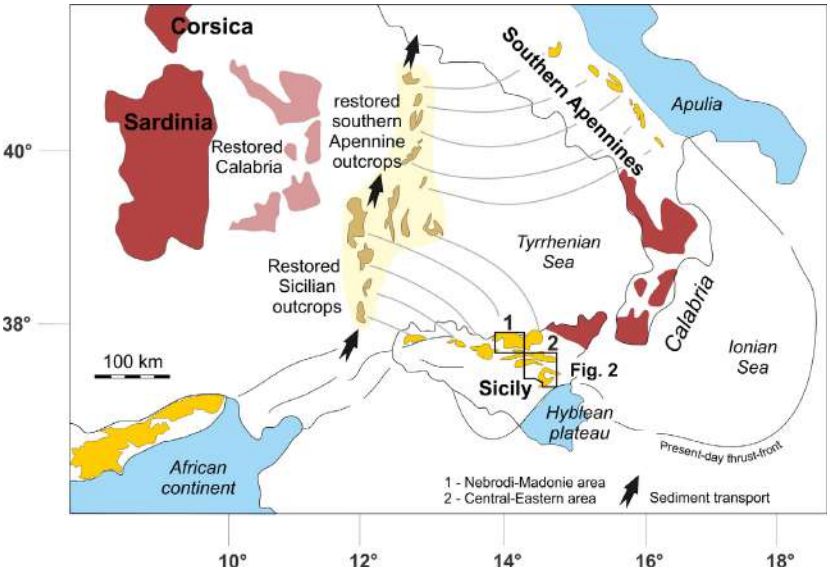



**Fig. 1.** Distribution of the Numidian outcrops in the Central Mediterranean. The outcrops in Sicily have experienced a *ca*. 100° CW rotation since deposition while outcrops in the Southern Apennines have experienced a similar CCW rotation (Speranza *et al*., 2003). The restored positions recover these rotations and show the outcrops ahead (E) of the restored basement terrane of the Calabrian arc. These Numidian outcrops have been swept onto the orogenic foreland (blue areas; African continent, Hyblean Plateau and Apulia). Boxed areas show location of (1) Nebrodi-Madonie area (northern Sicily) (Pinter *et al*., 2016), and (2) Central-Eastern area (this paper; Fig. 2a).

## The age of the Numidian in Central-East Sicily: new biostratigraphic data

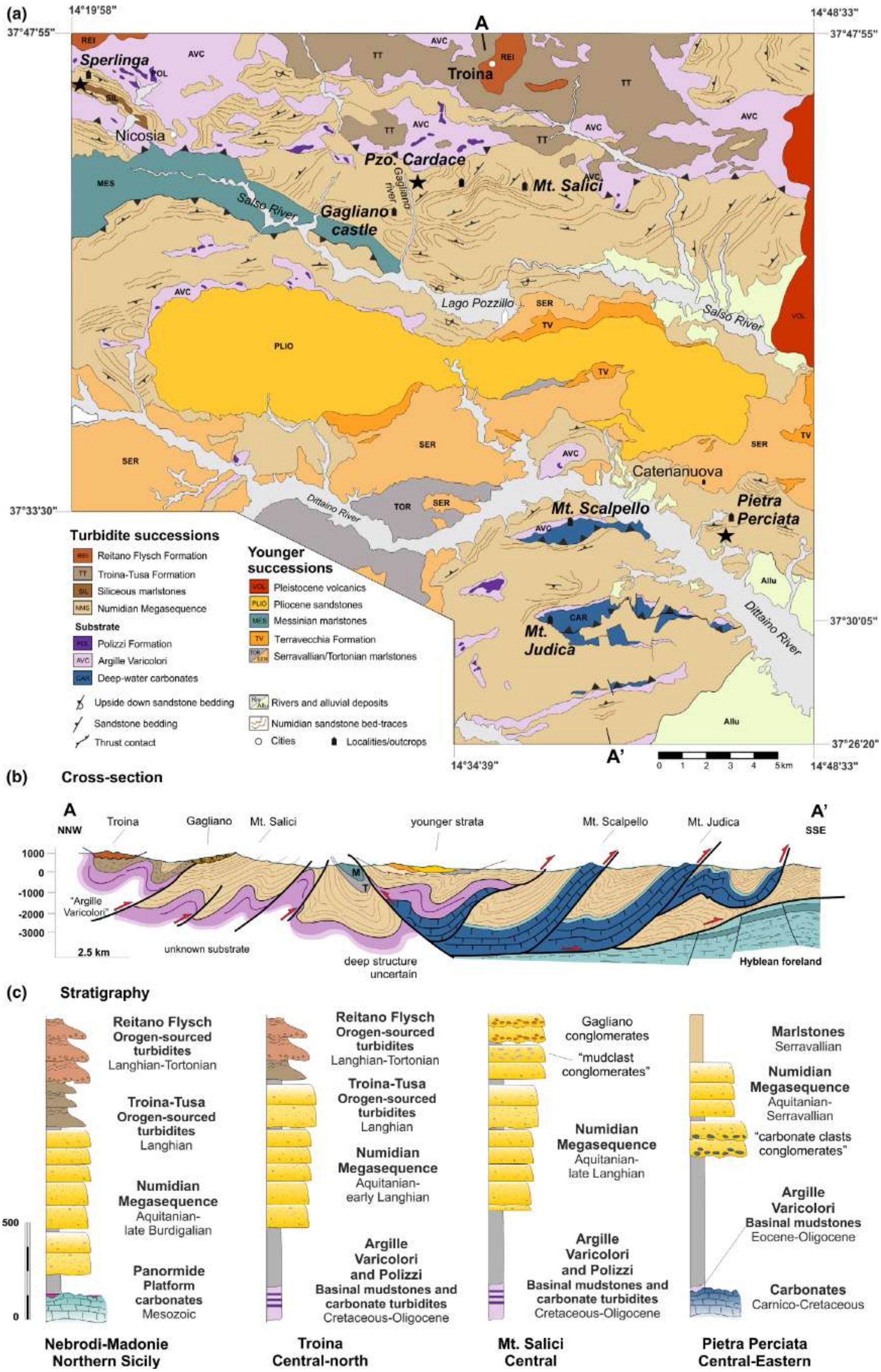
The Numidian is classically ascribed to late Oligocene to mid-Miocene age (Lentini *et al*., 1991; Carbone & Grasso, 2012) based on micropalaeontology. However, as with many turbidite successions, it is increasingly accepted that most of the fauna are reworked as the causative turbidity currents swept over and entrained slope and basin-floor mud (e.g. De Capoa *et al*., 2004). New biostratigraphic data presented by Pinter *et al*. (2016) have shown that the late Oligocene fauna is reworked into younger intervals, narrowing the age of the Numidian megasequence of northern Sicily to the early Miocene (Aquitanian-late Burdigalian). Consequently, we now reappraise the age of the Numidian in Central-East Sicily.

We have sampled the Sperlinga, Mt. Salici/Gagliano and Pietra Perciata sections (Fig. 2a) for biostratigraphic analysis (planktonic foraminifera and calcareous nannofossils). The sampling preparation and analysis took place at the Department of Biological, Geological and Environmental Sciences of the University of Catania. Samples for foraminifera analysis were washed and filtered in normal water through a 63 μm sieve. The residues, dried in an oven at 50°C, were analysed by distinguishing specimens at specific and supra-specific level. Smear slides for nannofossil analysis were prepared following standard methods (Haq & Lohmann, 1976; Rio *et al*., 1990; Catalano *et al*., 1996) and analysed with a Zeiss Axioscope microscope under magnification 1000X. Specifically, we performed a targeted count on genera *Sphenolithus* and *Helicosphaera*, which represent the biostratigraphically most relevant genera for the early to middle Miocene time interval (e.g. Fornaciari & Rio, 1996; Fornaciari *et al*., 1996; Foresi *et al*., 2011, 2014; Baldassini & Di Stefano, 2015, 2017). The results are presented below (Fig. 3).

### *Sperlinga section*

The Sperlinga marlstone section is characterized by interbedded fine-grained sandstones and siltstones that pass up into a calcareous succession, of thin-bedded micaceous sandstones interbedded with siliceous marlstones (the 'silexites' of Broquet, 1972). The siliceous content in

**Fig. 2.** (a) Geological map of Central-East Sicily showing the main lithological units mapped in this study, including the continuity of the Numidian bed-sets. (b) Cross-section showing the different Numidian substrates in the two study areas (*Argille Varicolori* for the Mt. Salici area and the deep-water carbonate succession for the Pietra Perciata area) and the main structures that are mapped in the region. Colour scheme follows the geological map presented in (a). The geological cross-section is based on surface and subsurface data (modified after Bianchi *et al*., 1987; Carbone *et al*., 1990). (c) Stratigraphy of the Nebrodi-Madonie area of Northern Sicily (after Pinter *et al*., 2016) and the Central-Eastern area of Sicily, showing main lithostratigraphic units and correspondent ages.


(a)
14°19'58"
14°48'33"
37°47'55"
37°33'30"
37°30'05"
37°26'20"
14°34'39"
A
A'
Sperlinga
Troina
Nicosia
Pzo. Cardace
Mt. Salici
Gagliano castle
Gagliano river
Salso River
Lago Pozzillo
Catenanuova
Dittaino River
Mt. Scalpello
Pietra Perciata
Mt. Judica
REI
AVC
TT
POL
SIL
MES
PLIO
SER
TV
VOL
TOR
CAR
Allu
0 1 2 3 4 5km
Turbidite successions
Reitano Flysch Formation
Troina-Tusa Formation
Siliceous marlstones
Numidian Megasequence
Substrate
Polizzi Formation
Argille Varicolori
Deep-water carbonates
Upside down sandstone bedding
Sandstone bedding
Thrust contact
Younger successions
Pleistocene volcanics
Pliocene sandstones
Messinian marlstones
Terravecchia Formation
Serravallian/Tortonian marlstones
Rivers and alluvial deposits
Numidian sandstone bed-traces
Cities
Localities/outcrops
(b) Cross-section
A
NNW
A'
SSE
Troina
Gagliano
Mt. Salici
younger strata
Mt. Scalpello
Mt. Judica
1000
0
-1000
-2000
-3000
"Argille Varicolori"
2.5 km
unknown substrate
deep structure uncertain
Hyblean foreland
M
T
(c) Stratigraphy
Reitano Flysch
Orogen-sourced turbidites
Langhian-Tortonian
Troina-Tusa
Orogen-sourced turbidites
Langhian
Numidian Megasequence
Aquitanian-late Burdigalian
Panormide Platform carbonates
Mesozoic
500
0
Nebrodi-Madonie
Northern Sicily
Reitano Flysch
Orogen-sourced turbidites
Langhian-Tortonian
Troina-Tusa
Orogen-sourced turbidites
Langhian
Numidian Megasequence
Aquitanian-early Langhian
Argille Varicolori and Polizzi
Basinal mudstones and carbonate turbidites
Cretaceous-Oligocene
Troina
Central-north
Gagliano conglomerates
"mudclast conglomerates"
Numidian Megasequence
Aquitanian-late Langhian
Argille Varicolori and Polizzi
Basinal mudstones and carbonate turbidites
Cretaceous-Oligocene
Mt. Salici
Central
Marlstones
Serravallian
Numidian Megasequence
Aquitanian-Serravallian
"carbonate clasts conglomerates"
Argille Varicolori
Basinal mudstones
Eocene-Oligocene
Carbonates
Carnico-Cretaceous
Pietra Perciata
Central-Eastern

the marlstone has been considered to be finely dispersed tuffaceous material (Faugères *et al.*, 1992). We collected six samples on the Sperlinga section (436723 m E; 4182325 m N; sampling location indicated by the Sperlinga star in Fig. 2a), with a spacing of 0.3–1 m between them. Within these samples, the planktonic foraminifera were rare and assemblages included long-range taxa, that are ascribed to MMi2 Biozone (Di Stefano *et al.*, 2015). The recognition of the calcareous nannofossil species *Sphenolithus belemnos* (in the youngest samples), of *Sphenolithus disbelemnos*, and the high frequency of *Helicosphaera carteri* associated with limited occurrence of *Helicosphaera euphratis* (in the lower part of the section), indicates deposition within the MNN2a to MNN3b interval zones of Fornaciari & Rio (1996), giving a late Aquitanian to middle Burdigalian age (Fig. 3) for the Sperlinga section.

### *Mt. Salici/Gagliano section*

The Mt. Salici/Gagliano section is characterized by grey siltstones with well-established faunal assemblage of both planktonic foraminifera (Amore, 1969; this paper) and calcareous nannofossils (Fornaciari *et al.*, 1996; this paper). These siltstones crop out towards the top of the Numidian succession in the Mt. Salici section. We collected 10 samples with 1 m spacing along the Gagliano river (460404 m E; 4174058 m N; sampling location indicated by the star near Gagliano river in Fig. 2a). Considering the planktonic foraminifera the presence of the species *Globigerinoides sicanus* (3 apertures) at the bottom of the section, the recognition of high frequency of *Paragloborotalia siakensis* (base of *P. siakensis* Acme 'a'; Iaccarino *et al.*, 2011) in the middle of the section, and the recognition of *Praeorbulina glomerosa curva* in the youngest part of the sampled interval, establishes the deposition of the re-analysed deposits at Mt. Salici/Gagliano to be latest Burdigalian to middle Langhian in age. This corresponds to the MMi4a–MMi4c biozones of Iaccarino *et al.* (2011). As for the calcareous nannofossils, the oldest sampled layers contain the *Sphenolithus heteromorphus* paracme interval. This is overlain by an interval of common distribution of *S. heteromorphus* and very rare occurrence of *Helicosphaera ampliaperta* specimens, that passes up into intervals with the common presence of *H. walbersdorfensis* as reported by Fornaciari *et al.* (1996). The bio-chronostratigraphic data place the section between the early Langhian to earliest Serravallian, corresponding to the MNN4c to MNN5c biozonal interval of Iaccarino *et al.* (2011). The combination of bio-chronostratigraphic results obtained here together with those gathered from literature, frames the age of the Mt. Salici/Gagliano section between the early Langhian to earliest Serravallian stages (Fig. 3), with the underlying (largely barren) sandstones a little older (presumably late Burdigalian). Detailed biostratigraphic data are presented in the Appendix S1.

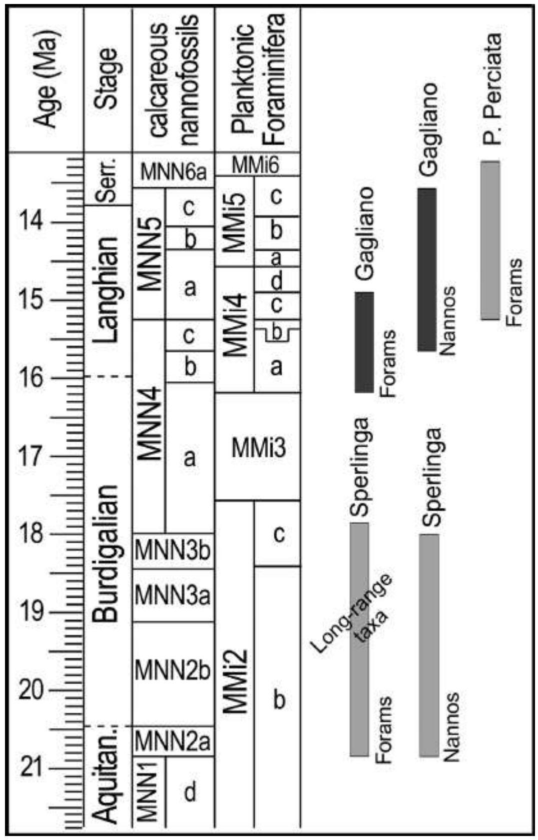



**Fig. 3.** Depositional intervals recognized in the Sperlinga, Mt. Salici/Gagliano and Pietra Perciata sections. Previous studies indicate a younger age of early Serravallian for the top of the Gagliano section (e.g. Amore, 1969; Fornaciari *et al.*, 1996). The calcareous nannofossil zones are from Fornaciari & Rio (1996), Fornaciari *et al.* (1996) and Iaccarino *et al.* (2011). The chronology of the bio-horizons is from Sprovieri *et al.* (2002), Abdul Aziz *et al.* (2008), Turco *et al.* (2011), Backman *et al.* (2012) and Foresi *et al.* (2014). The planktonic foraminifera zones are from Iaccarino *et al.* (2007, 2011) and Foresi *et al.* (2014). The chronology of the bio-horizons is from Lourens *et al.* (2004), Abdul Aziz *et al.* (2008), Turco *et al.* (2011), Wade *et al.* (2011) and Foresi *et al.* (2014).

### *Pietra Perciata section*

The Pietra Perciata section is located at approximately 15 km SE of Lago Pozzillo, near Catenanuova village. The section is characterized by a thick succession of Numidian fine-grained siltstones with rare sandstone beds at the base of the section (dated early Langhian in Carbone *et al.*, 1990) and coarse sandstones towards the top. The Numidian succession passes upwards into marlstones of Serravallian age (Carbone *et al.*, 1990). We collected 10 samples from the basal fine-grained deposits of the Pietra

Perciata section (477310 m E; 4155449 m N; sampling location indicated by the Pietra Perciata star in Fig. 2a), with a spacing of 1–2 m between them. Within these samples, planktonic foraminifera were absent or agglutinated, and the calcareous nannofossils were very rare and poorly preserved, preventing age determination. Therefore, as the succession passes up into overlying Serravallian marlstones without obvious stratigraphic breaks, we consider the end of sedimentation of the Numidian in Pietra Perciata section to be early Serravallian in age (Carbone *et al.*, 1990; Fig. 3).

*Biostratigraphic summary*

The new biostratigraphic data presented here indicate that the Numidian of Central-East Sicily ranges overall from late Aquitanian to early Serravallian. However, the studied sections indicate strongly diachronous Numidian deposition in the area. For example, during the Burdigalian, whilst sand sedimentation occurred in the Mt. Salici/Gagliano section, calcareous sedimentation prevailed in the Sperlinga section. And, the Numidian in the Pietra Perciata section is younger than the Mt. Salici/Gagliano, indicating that sand sedimentation in the Mt. Salici/Gagliano finished earlier than in the Pietra Perciata. This young trend of Numidian turbidites from North to South (present-day orientation of Sicily) is also reinforced by our previous work in northern Sicily, where the Numidian retains the oldest successions of Aquitanian to late Burdigalian (Pinter *et al.*, 2016). Considering the age of the Numidian of Sicily and its outcrop distribution, we observe that the sand sedimentation switched progressively from northern Sicily (Nebrodi-Madonie), towards central Sicily (Sperlinga and Mt. Salici/Gagliano) and ultimately finished in Eastern Sicily (Pietra Perciata), with no outcrops further South. We now investigate the sedimentology and thickness of these same three sections to explore whether the diachronous deposition is associated with substrate configuration (Fig. 4).

## LITHOFACIES OF THE NUMIDIAN MEGASEQUENCE OF CENTRAL-EAST SICILY

The majority of the Numidian megasequence lithofacies has been previously described and interpreted by Pinter *et al.* (2016) with basis on extensive work carried out in northern Sicily. The facies description and interpretations are summarized in Table 1. In this section, we briefly describe the facies and discuss differences and similarities between the Numidian megasequence of the Northern and Central-East Sicily. We also describe and interpret distinct facies which are not reported for the Numidian megasequence in the previous work.

### Sandstones

The sandstones are well-sorted, ungraded beds of upper-medium or coarse sandstones. They occur in amalgamated bed-sets of up to 50 m thick, with individual beds of up to 2 m thick. Syn-depositional dewatering generally obscures primary depositional fabrics, but where absent, primary banding and parallel lamination occur. These imply aggradation. Evidence for sediment bypass is clear in the bed-tops by the abrupt grain-size breaks, generally from medium sand to silt. This implies that either the missing part of the grain-size spectrum has bypassed the area or, somewhat implausibly, that it was retained up-dip (already filtered out by some mechanism in a stepped or topographically complex slope profile; Spychala *et al.*, 2015; Jobe *et al.*, 2017; Wang *et al.*, 2017). We interpret bypass to have occurred along the main fairway, as proposed by Pinter *et al.* (2016) for the well-sorted coarse sandstones (Lithofacies B2) of northern Sicily. What is interesting is that the sandstones retain the same characteristics of those deposited upstream (Northern Sicily) indicating that the sand is not being deposited by waning flows, but somehow the turbidity currents are still energetic to carry coarse sand downdip.

### Quartzitic conglomerates

The conglomerates are matrix-supported, normally graded beds of pebbles to coarse sands. They occur in amalgamated bed-sets of up to 5 m thick, with individual beds of up to 1 m thick, and form lenticular units (*ca.* 200 m) overlying erosion surfaces that incise (*ca.* 20 cm) into underlying sandstones. In contrast, the coarse sand component on the top of these beds can be traced laterally into the rest of the bed-set. Pebbles are up to 5 cm, subrounded to rounded, with moderate sphericity, composed exclusively by quartz, with no intraformational material. Pebbly lags are common within the sandstones. The conglomerates are unlikely to represent rapid sedimentation since they preserve structures such weak normal gradation and crude orientation of pebbles. The pebbly lags also support evidence for bypassing flows, because their tops generally display a grain-size break. The conglomerates are consistent with Lithofacies B1 of Northern Sicily (Pinter *et al.*, 2016) and correspond to a thalweg position within the fairway.

### Conglomerates of reworked substrate

*Mudclast conglomerates*

The mudclast conglomerates are matrix-supported coarse-grained sandstones with abundant mudclasts. They occur interbedded with coarse to granular sandstones, with individual beds of up to 1.5 m thick, as

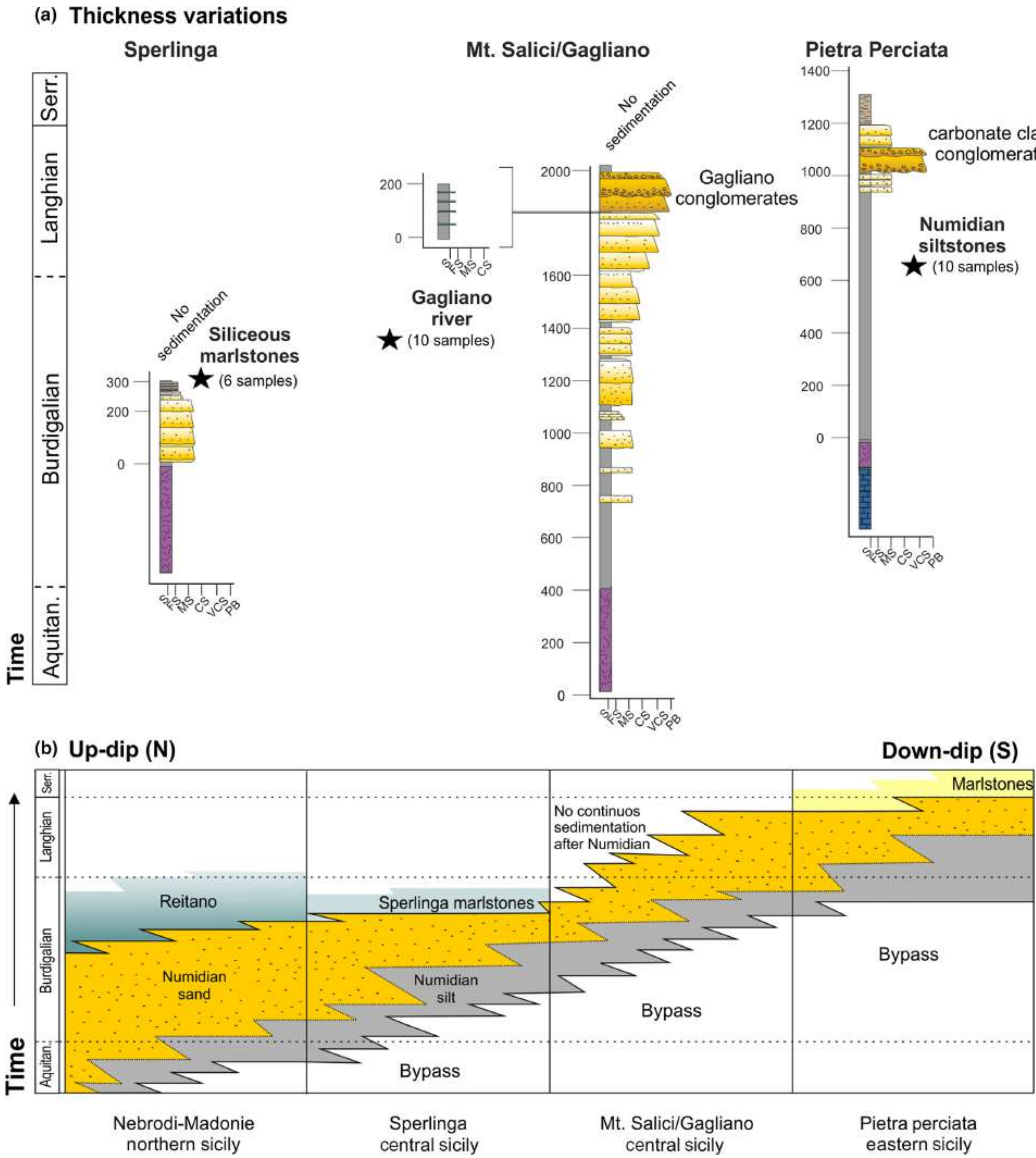



**Fig. 4.** (a) Sedimentary logs of the studied sections showing thickness variations, timing of the Numidian sedimentation and location of the samples collected for biostratigraphic analysis. Sperlinga section includes 300 m of Numidian succession deposited on top of the substrate of *Argille Varicolori* and finishing during the mid-Burdigalian; Mt. Salici and Gagliano sections form a composite log that includes more than 2000 m of the Numidian succession with sedimentation finishing after Langhian; Pietra Perciata section comprises 1500 m of the Numidian succession deposited on top of a substrate composed by deep-water carbonates and thin succession of *Argille Varicolori* and finishing during early Serravallian. (b) Diagram showing the timing and distribution of the Numidian sandstone sedimentation in Sicily. Considered sections are displayed from up-dip to down-dip positions and show strong diachroneity of Numidian sandstone sedimentation.

tabular units or lenticular units formed by shallow erosion (*ca.* 15 cm). The largest outcrop is found towards the top of the Mt. Salici section, otherwise it is not common within the Numidian megasequence. Here, we interpret the mudclast conglomerates as product of substrate erosion of passing flows. The predominantly bypassing

**Table 1.** Summary of the lithofacies of the Numidian megasequence of the Nebrodi-Madonie area (northern Sicily) previously proposed by Pinter *et al.* (2016)

| Group | Lithofacies | Sedimentary structures | Bed shape | Thickness | Interpretation |
|---|---|---|---|---|---|
| Group A<br>Carbonates | **Lithofacies A1**<br>Carbonate breccias<br>Clast-supported conglomerates | Chaotic<br>Clast alignment to bedding<br>Weak normal grading | Wedge-shaped<br>Erosive base (10–15 cm) | 0.5–3 m thick bed-sets >5 m | Carbonate breccias are repeated rock-falls down an active submarine slope. They are deposited laterally to the main turbidity current conduit, therefore interbedded with Lithofacies B4, C1 and C3. |
| Group B<br>Quartz arenites | **Lithofacies B1**<br>Pebbly conglomerates<br>Clast to matrix-supported conglomerates | Clast alignment to bedding<br>Weak normal grading | Lenticular<br>Erosive base (max 10 cm) | 0.1–1 m thick | Pebbly conglomerates are deposits of bed-load coarse sediments accumulated along the main flow axis of the turbidity current. Channel-fills? |
| | **Lithofacies B2**<br>Well-sorted coarse sandstones | Ungraded<br>Parallel lamination<br>Dewatering | Tabular<br>Sharp base | 0.5–2 m thick bed-sets >10 m | Well-sorted coarse sandstones are deposited along the main flow axis of the turbidity current. These deposits are not restricted to channels but stack to form highly elongated aggradational lobes. |
| | **Lithofacies B3**<br>Graded sandstones | Normal grading<br>Parallel lamination<br>Ripples/convolute lamination<br>Dewatering | Tabular<br>Sharp base | 0.1–0.9 m thick bed-sets of 2 m | Deposits of locally waning turbidity currents and/or smaller turbidity currents that behave as generally unconfined, with respect to those that deposited Lithofacies B1 and B2. |
| | **Lithofacies B4**<br>Thin-bedded medium to fine sandstones | Normal grading<br>Parallel lamination<br>Ripples/convolute lamination<br>Dewatering | Tabular<br>Sharp base<br>Loaded | Sandstones 0.01–0.2 m thick bed-sets of 0.25 m | Thin-bedded medium to fine sandstones are deposits from the edges of the turbidity currents that are otherwise transversing the basin. Thin-bedded sandstones are result of overflow beyond the main conduit. |
| Group C<br>Silty successions | **Lithofacies C1**<br>Heterolithics | Ungraded<br>Weak normal grading<br>Parallel lamination<br>Ripples/convolute lamination | Tabular<br>Local erosive (1 cm) Loaded | Sandstones 0.01–0.06 m thick | Heterolithics are deposits accumulated at the flanks of the main turbidity current conduits and/or originated from the tails of the otherwise bypassing turbidity currents. |
| | **Lithofacies C2**<br>Slumps | Folded and disrupted sandstones<br>Cross-cutting geometries<br>Sand injectites | Chaotic<br>Irregular | 1–25 m thick | Slumps are result of local deformation and/or remobilization of sandstones and siltstones related to intra-basin slope instability. |
| | **Lithofacies C3**<br>Siltstones | Ungraded<br>Weak normal grading | Tabular | Beds <1 cm thick | Deposits from highly dilute flows, most probably from overflow beyond the main turbidity current conduit that precedes the arrival of the main sand -bearing flows in these parts of the basin network. |

nature of flows coupled with a lack of fine-grained sediment deposition within the sand-fairways indicates that mudclasts were either transported from upstream or sourced locally from intra-basin slopes. This lithofacies is commonly described from tectonically active compressional settings with flows either crossing thrust anticlines (Morley, 2009) or interacting with the bounding slope (McCaffrey & Kneller, 2004; Brunt *et al.*, 2013).

*Carbonate clast conglomerates*

The carbonate clast conglomerates are matrix-supported coarse-grained to gravely sandstones with clasts sourced from the carbonate substrate (*Polizzi Formation*). They occur as broad-lenticular deposits, incised (*ca.* 20 cm) into the underlying sandstones, with individual beds of up to 1.5 m thick, found at the base of Pietra Perciata section (Fig. 11). Carbonate clasts interbedded with Numidian fine-grained facies (Lithofacies A1) are described in northern Sicily and interpreted as being the result of submarine mass-wasting of bed-rock sourced laterally from thrust-related folds and shed into the sand-fairway *(Pinter et al.,* 2016). At Pietra Perciata, however, the carbonate clasts are interpreted here as derived from erosion of soft substrate (*Polizzi Formation*) that are transported downstream along the main sand-fairway and sedimented together with coarse-grained quartz sand (matrix). The incised character of the beds is consistent with coarse, channel-fill deposits (Mayall *et al.*, 2006). Similar facies have been described in the Madonie section in northern Sicily as scour-fill found along the base of the palaeoslope (Pinter *et al.*, 2016). This type of substrate reworking has been attributed to localized incision of bathymetric highs in complex basins such as the Sinu Prism (e.g. Vinnels *et al.*, 2010).

## Fine-grained facies

Laterally extensive packages of muds, silts and thin-bedded fine sandstones comprise our fine-grained facies. Sandstone beds range from 1 to 5 cm in thickness and are composed of well-sorted fine to very fine-grained sand. They occur in tabular deposits with no or very shallow erosion (*ca.* 1 cm) at the sandstone bed bases. The fine-grained facies packages are found intercalated with thick sandstones and towards the marginal areas of the basin (off sand-fairway). These facies are equivalent to the Lithofacies B4 described for the Numidian megasequence of northern Sicily (Pinter *et al.*, 2016). Here, we interpret the fine-grained facies as recording smaller turbidity currents reaching the basin. These facies are also associated with flow stripping as a response to the interaction of turbidity currents with basin-floor topography (Spychala *et al.*, 2015; Jobe *et al.*, 2017; Wang *et al.*, 2017). In this case, the confinement of the coarser portion of the turbidity currents by the basin-floor structures prevents sand-laden flows over barriers, but the finer portion of the turbidity currents carried in suspension is able to fractionate from the coarser sediment load with deposition occurring on top of intra-basin highs or areas marginal to the main sand-fairway. In other (structurally unconfined) settings, such facies might be interpreted as being aggradational lobe-fringe or outer extra-channel (overbank) deposits (Spychala *et al.*, 2017). However, for structurally confined systems we suggest that they represent the distal/lateral portions of flows that were otherwise largely captured up-system or are fall-out from the margins and tails of otherwise bypassing flows.

## Siliceous marlstones

Siliceous marlstones form thin-laminated or massive grey beds up to 20 cm thick interbedded with fine sandstones up to 5 cm thick. They crop out on top of the Numidian megasequence in the Sperlinga section. There is no report of similar facies in the Numidian megasequence of Northern Sicily. The siliceous marlstones are likely to represent periods of very low sedimentation (Lentini *et al.*, 1991) presumably away from the main siliciclastic input in the area, therefore we interpret this facies as deposited under 'sediment-starved' conditions in result of the re-routing of the sand-fairway.

## Siltstones

Micaceous grey siltstones interbedded with occasional marlstones comprise this lithofacies. They form thinly laminated (<1 cm) tabular deposits with millimetre-scale intercalation with clays. Siltstones are found towards the Mt. Salici section, by the Gagliano River, in Central Sicily. These facies occur interbedded or lateral to the thick sandstone packages and are equivalent to the Lithofacies C3 described by Pinter *et al.* (2016). Here, we interpret this facies to represent either periods of non-sand deposition along the sand-fairways or sedimentation of highly dilute flows that represent the tails of multiple flows deposited down-system.

# THICKNESS VARIATIONS

Thickness variations in the Numidian megasequence of Central-East Sicily are shown in Fig. 4. Thicknesses were determined from three sedimentary logs with a correlation datum taken at the top of the Numidian substrate, geological maps and subsurface data (Bianchi *et al.*, 1987; Lentini *et al.*, 1990; Bello *et al.*, 2000), boreholes (ENI-AGIP, 1972) and biostratigraphy (presented above). Here, we briefly describe the Numidian facies and illustrate the difference in thickness of the turbidite succession encountered in individual sections.

## Sperlinga section

The 300 m thick Numidian section at Sperlinga (Fig. 5a, b) lies on mudstones of the *Argille Varicolori* (Fig. 6c). It is characterized by tabular sandstone bed-sets interbedded with finer intervals of thin-bedded sandstones and siltstones of up to 2 m, rarely exposed. Above this, the section dominantly comprises bed-sets of amalgamated sandstones up to 20 m thick, with individual sandstones beds up to 2 m thick. In general, the beds are ungraded but preserve parallel lamination (Fig. 6d). The sandstones are quarzitic, medium to coarse-grained, well-sorted. Towards the top of the section, the sandstones are abruptly replaced by a calcareous succession, the Sperlinga siliceous marlstones (Fig. 6e) described above. The siliceous marlstones represent the top of the Numidian in the Sperlinga section and, as noted earlier, are late Aquitanian to middle Burdigalian in age. We consider these marlstones to represent the stratigraphic top of the Numidian sequence at Sperlinga with no deposition of quartz sandstones above this interval.

## Mt. Salici section

The 2000 m thick Numidian section at Mt. Salici (Fig. 7) lies on the mudstones of the *Argille Varicolori*, penetrated by boreholes (ENI-AGIP, 1972) at more than 2000 m depth. The lower *ca.* 800 m of this succession is dominantly mudstone and siltstone, with thin fine sandstone interbeds. Thick (>1 m), amalgamated units of medium-coarse sandstone come in abruptly and form bed-sets of amalgamated sandstones of up to 40 m thick, with individual sandstone beds up to 1.5 m. In general, beds are ungraded or weakly graded. The whole section coarsens upwards becoming increasingly pebbly. Sandstone units can be mapped laterally and shown to underlie the Langhian age siltstone succession near Gagliano castle. This section is down-system in relation to Sperlinga.

## Pietra Perciata section

This section is down-system in relation to Mt. Salici and represents the most ‘distal’ deposits in our study. The 1400 m thick Numidian section at Pietra Perciata (Fig. 8) lies on a thin layer of *Argille Varicolori* deposited on top of a Mesozoic-Eocene succession of deep-basin carbonates and local cherts. The lower 800 m is characterized by brown claystones, and siltstones. The first Numidian sandstone crops out *ca.* 800 m into the section from its substrate. The transition up into the coarse-grained sand-rich interval is abrupt. These upper units are formed by a 20 m thick bed-set of amalgamated sandstones, with individual sandstone beds up to 1 m thick. In general, beds are weakly graded, with convolute lamination. The sandstones are fine to medium-grained, with a pebbly interval and frequent coarse lags developed at the bases of the lower sandstone beds. These quartz sandstones pass up into poorly exposed marlstones of Serravallian age (Carbone *et al.*, 1990).

## Interpretation as thrust-top sedimentation

The three sections described above show significant differences in thickness and depositional style. The Sperlinga and Mt. Salici sections lie along strike from each other, some 15 km apart and within the same broad tract of Numidian outcrop. Existing mapping (e.g. Carbone *et al.*, 1990) shows near-continuity of cliff and escarpment-forming bed-sets of amalgamated sandstones. This map-continuity of scarp-formed bed-sets and the absence of major thrust-sheets of substrate strongly suggest that, although the successions are deformed, they form part of the same basin. At Sperlinga, the entire Numidian succession is just 300 m thick and almost exclusively represented by thick, amalgamated sandstones. Sand input into this part of the basin terminated in the Burdigalian, followed by the siliceous marlstones deposits. In contrast, the succession at Mt Salici is over 2 km thick, with the main sandstones only entering the basin after deposition of 800 m of fine-grained sediment. In contrast to the Sperlinga section, the Mt. Salici area coarsens upwards with thick gravels dominating. Comparing the two sites, these variations are certainly not consistent with Numidian deposition occurring across an unstructured basin-floor, as proposed by the extant model for the system (e.g. Guerrera *et al.*, 2012). Differential thickness and facies variations between the sites can indicate differential subsidence and/or significant basin-floor topography. That these sections and that at Pietra Perciata are distinct and of different ages suggests that turbidity currents were routed through the region along temporally and spatial restricted pathways, creating zones of accumulation, erosion and bypass of sediments. It is with a view of reconstructing these sediment pathways that we now examine the facies and infer depositional processes at Mt. Salici and Pietra Perciata.

# SEDIMENTOLOGY AND ARCHITECTURE OF NUMIDIAN MEGASEQUENCE OF CENTRAL-EAST SICILY

The sedimentological data presented here for Mt. Salici and Pietra Perciata are derived from sedimentary logs at 1 : 100 scale, which allow characterization of the sedimentary facies, bed thickness, grain-size and sandstone/siltstone ratio. The architectural information comes from

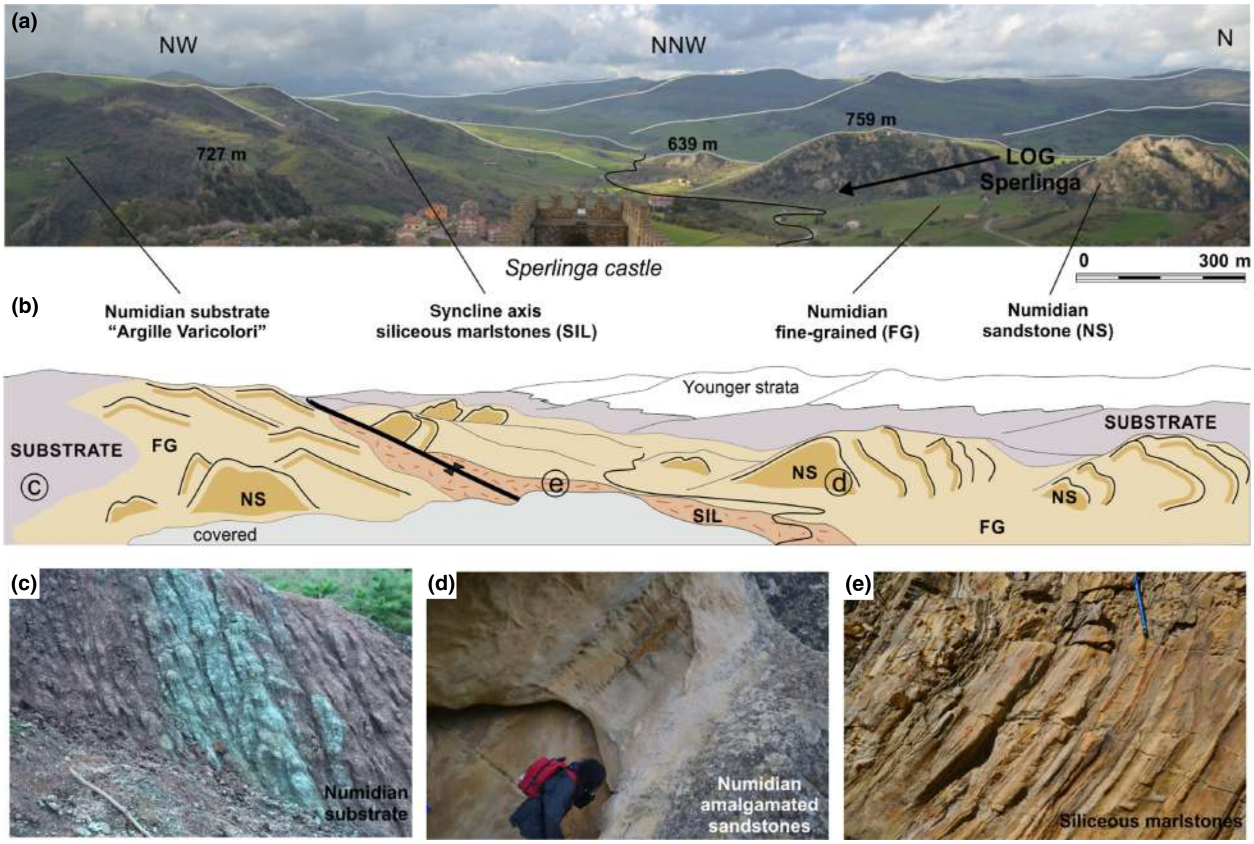



**Fig. 5.** (a) Panoramic view of the Sperlinga area and (b) annotated interpretation. The view shows a tight syncline with Numidian sandstone beds dipping towards the valley, where the siliceous marlstones are deposited; (c) Outcrop example of the Numidian substrate of Central Sicily – the *Argille Varicolori*; (d) Bed-sets of amalgamated Numidian sandstones, characteristic of the Sperlinga section. (e) Outcrop of the siliceous marlstones at the top of the Sperlinga section.

a combination of field mapping and structural observations and is presented as interpreted panels. The area is covered by a previous geological map (Carbone *et al.*, 1990) and regional cross-sections (Bianchi *et al.*, 1987; Bello *et al.*, 2000), which although consulted, were strongly modified.

## Mt. Salici section

The sedimentology of the Mt. Salici section (Fig. 8) comes from a composite stratigraphic log collected from the Mt. Salici section (466822 m E; 4174708 m N) and the Gagliano castle section (459217 m E; 4174067 m N). The Mt. Salici section crops out from the Lago Pozzillo up to the summit of Mt. Salici (1142 m), comprising more than 1000 m of continuous stratigraphic section. The section dips northwards and crops out in a south-facing cliff section (Fig. 6a). The section trends NW-SE, approximately perpendicular to palaeoflow. Flute cast and grooves on exposed sandstone bases were the main palaeoflow indicator, as other features (e.g. ripples) are rare (Thomas *et al.*, 2010).

The lower part of the section is dominated by a thick sequence of fine-grained deposits with tabular sandstone packages. The upper part of the sequence, which forms the focus of this study, is dominated by sheet-like thick, coarse-grained sandstones. The sedimentology of the upper part of the sequence on Mt. Salici is shown in a representative composite log MS1 (Fig. 8) and correspondent photos (Fig. 9).

The overall character of the MS1 section (Fig. 8) is dominated by ungraded, amalgamated sandstone beds, up to 40 m thick, separated by thinner-bedded sandstone and siltstone intervals (Fig. 9a). The sandstones are composed of ultra-mature sediments (>99% quartz). Tabular, amalgamated sandstone bed-sets have demonstrable lateral continuity of more than 5 km, with only local evidence of erosion at bed bases. The log is divided into five packages labelled A to M from the base upwards (Fig. 8). Sandstone packages at the base of the log (A and B) comprise individual beds 0.1–2 m in thickness. Composite bed-sets of amalgamated sandstones measure up to 20 m. The sandstones are medium-grained and well-sorted (Fig. 9b). The beds are non-graded or weakly normally

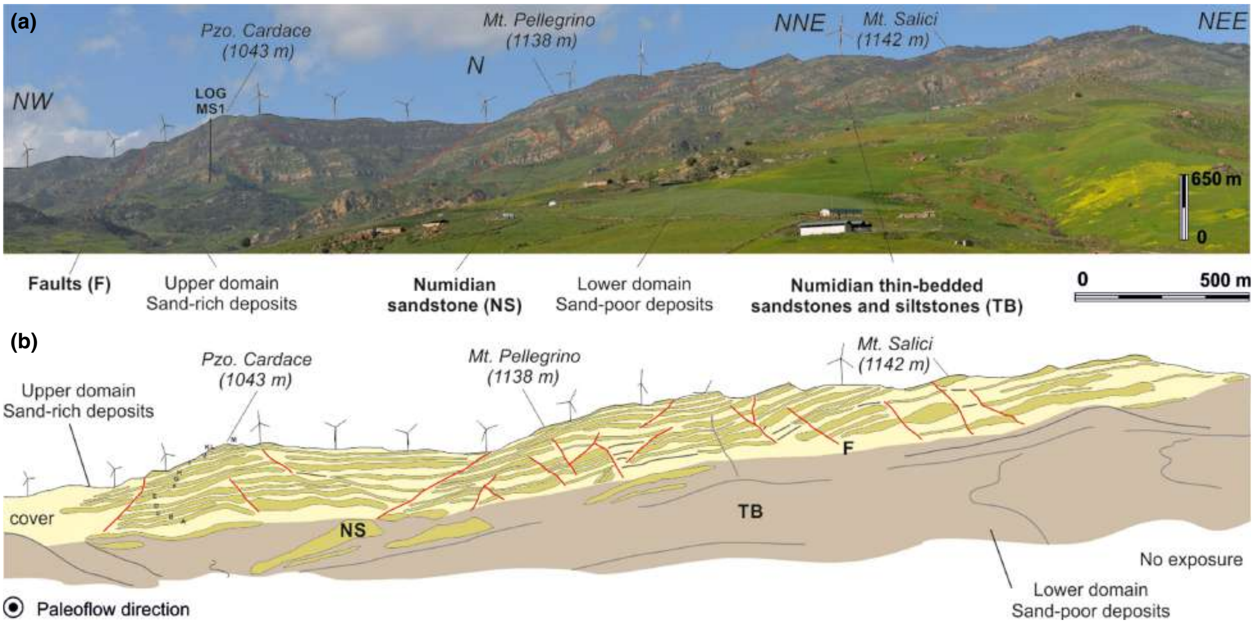



**Fig. 6.** (a) Panoramic view of the Mt. Salici section and (b) annotated interpretation. The section is represented by a lower package of sand-poor lithofacies at the base and by an upper package of sand-rich lithofacies. The Numidian sandstones display a tabular geometry and can be correlated laterally for the full extent of the outcrop. Some beds are disrupted by later faults. The location of log MS1 (Fig. 8) is shown on (a), together with the main localities of the section.

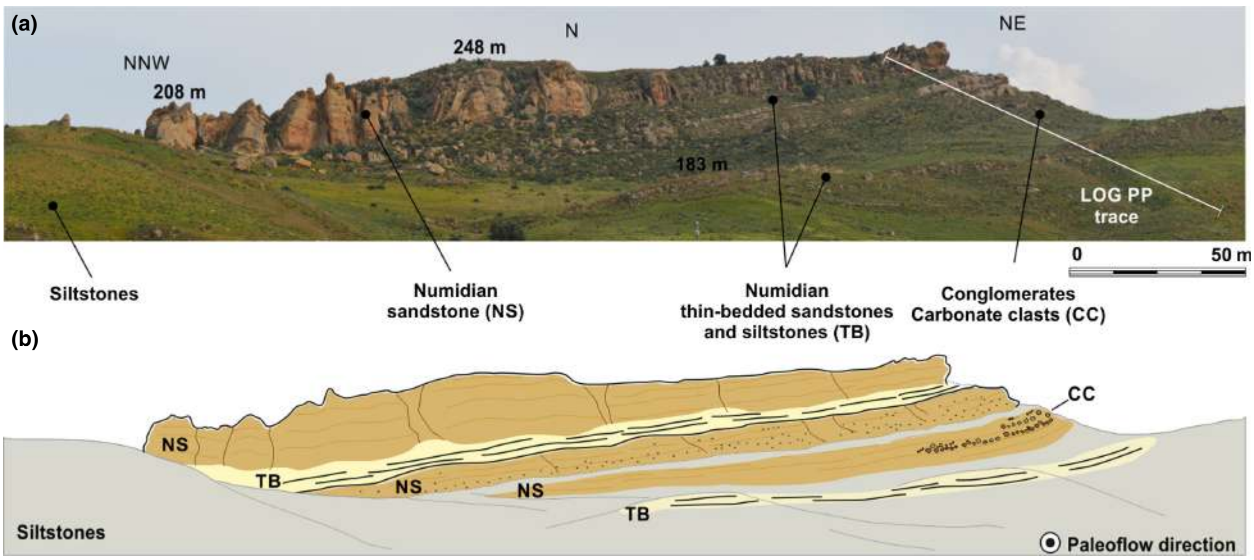



**Fig. 7.** (a) Panoramic view of the Pietra Perciata section and (b) annotated interpretation. The section is represented by a prominent sandstone package (several bed-sets of amalgamated sandstones) cropping out on top of a thin-bedded sandstone and siltstone succession. Palaeocurrent out of the page. The location of the log PP (Pietra Perciata section; Fig. 11) is shown on (a). The outcrop location of the conglomerates of reworked substrate (carbonate clasts derived from the *Polizzi Formation* are indicated by CC in (b).

graded. Some normally graded beds display parallel and convolute lamination towards the top (Fig. 9c). Bed bases are slightly erosive (ca. 2 cm) or sharp. Bed-tops are sharp or commonly obscured by amalgamation. The grain-size increases in package C. The coarser sandstones packages (C, D and E) comprise individual beds 0.15–6 m in thickness. Composite bed-sets of amalgamated coarse sandstones measure up to 25 m. The sandstones are characterized by medium to coarse well-sorted sands, with common parallel lamination (Fig. 9d). Outsized clasts of granules and up to 1 cm pebble-sizes are commonly dispersed throughout sandstones. The coarser fraction of

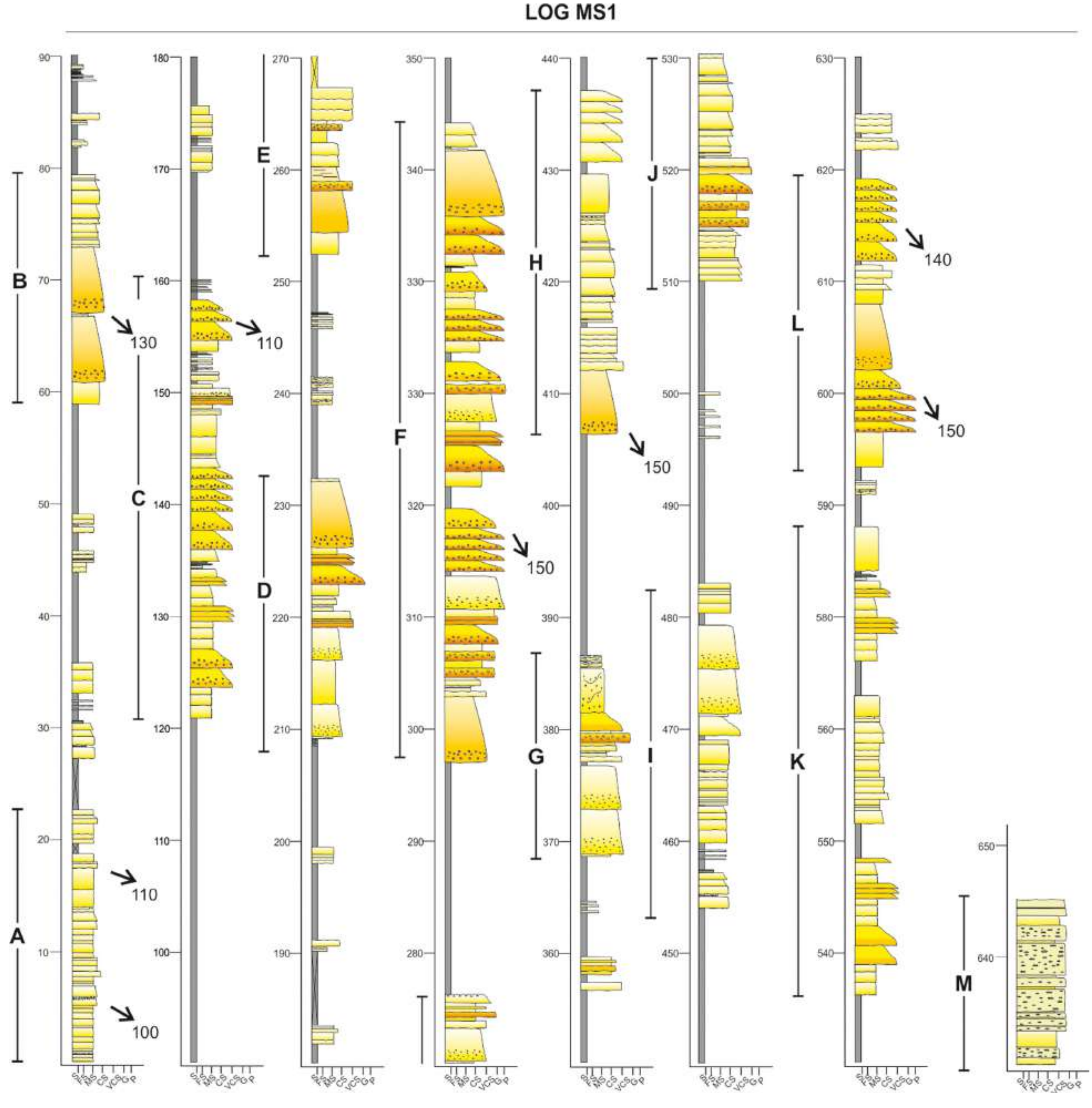



**Fig. 8.** Sedimentary log MS1 (see log location in Fig. 6a). The sedimentary log is subdivided into sandstone packages labelled A to M. Palaeocurrents are presented as arrows along the sedimentary log and their values represent present-day measurements (unrestored rotation).

very coarse to granular grain-size is found predominately towards bed bases (Fig. 9e). Beds are weakly normally graded with crude parallel lamination. Beds bases are slightly erosive (*ca*. 5 cm). Towards the middle of the section, the proportion of granular and pebbly material increases. The sandstone packages (F to L) comprise individual beds 0.2–7 m thick and form composite sandstone bed-sets up to 15 m thick. The sandstones are characterized by coarse to very coarse grain-size, with granules and pebbles found at bed bases. The coarser grain-size is typically 1–2 cm, poorly sorted, and exclusively composed of quartz. The beds are non-graded or weakly normally graded, with grain alignment sub-parallel to bedding in the coarser fraction. Bed bases are locally erosive (*ca*. 10 cm). The top of the section is characterized by a distinct lithofacies (package M; Fig. 8) which comprises intercalated clean coarse sandstones and mudclast conglomerates (Fig. 9f). The sandstones comprise individual beds of 0.1–2 m in thickness, of poorly sorted, very coarse to granular grain-size material, with common floating outsized pebble clasts. The beds are non-graded or weakly normally graded, with common parallel lamination. Bed bases are weakly erosive (*ca*. 5 cm) and commonly loaded into mudclast conglomerates. Mudclast conglomerates (Fig. 9f) are matrix-supported with a granular sandstones matrix. Mudclasts are typically up to 15 cm, angular to elongate and exclusively composed by siltstones. Some bigger siltstone rafts occur in the section with sizes of up to 1 m. The granular matrix is poorly sorted with outsized pebbles of up to 3 cm. The beds are non-graded. Bed bases are sharp or locally erosive (*ca*. 10 cm), with frequent soft-sediment deformation.

### *Gagliano Castle section*

The coarse units of Mt. Salici can be mapped westwards towards Gagliano castle, where they can be traced into the base of the now steeply dipping (*ca*. 80°) Gagliano castle section. The Gagliano castle outcrop is stratigraphically above than the Mt. Salici section, and thus represents the very top of the succession in the area. The Gagliano castle section (Log GAG; Fig. 10) records the coarsest lithofacies in the Numidian of Central-East Sicily comprising individual beds of coarse pebbly conglomerates (Fig. 10a) up to 5 m in thickness. The section is a composite of amalgamated bed-sets of sandstones up to 50 m in thickness. Sandstones are very coarse to granular, with pebbles found along bed bases, and are ultra-mature (>99% quartz). Beds are normally graded (Fig. 10b), but rarely transition into grain-sizes finer than medium. Bed bases are locally erosive (*ca*. 10 cm) and pebbles are frequently found as scour-fills (lags). Soft-sediment deformation, especially loading and foundering, is common (Fig. 10c).

## Vertical variations in the Mt. Salici-Gagliano section

In the Mt. Salici-Gagliano section, a coarsening upward trend is observed. The lower part of the section is characterized by thin sandstones interbedded with siltstones (low N/G) and the upper part of the section is characterized by sand-conglomerate units with little or no siltstone present (high N/G). The passage from the lower part towards the upper part is marked by the first sandstone in the section, which is denoted by the start of log MS1 (Fig. 8). The mudclast conglomerates cropping out towards the top of the section (package M of log MS1) record a distinct lithofacies towards the top of the section, with abundant mudclasts cemented together with coarse sandstones and pebbly conglomerates. These deposits are still characterized by clean and ultra-mature quartz grains. The stratigraphic evolution of the basin is further detailed by the subsequent log GAG (Fig. 10). Stratigraphically on top of the mudclast conglomerates is the Gagliano castle section, which is characterized by a thick package of amalgamated pebbly conglomerates. There is no change in the depositional style in the vertical section

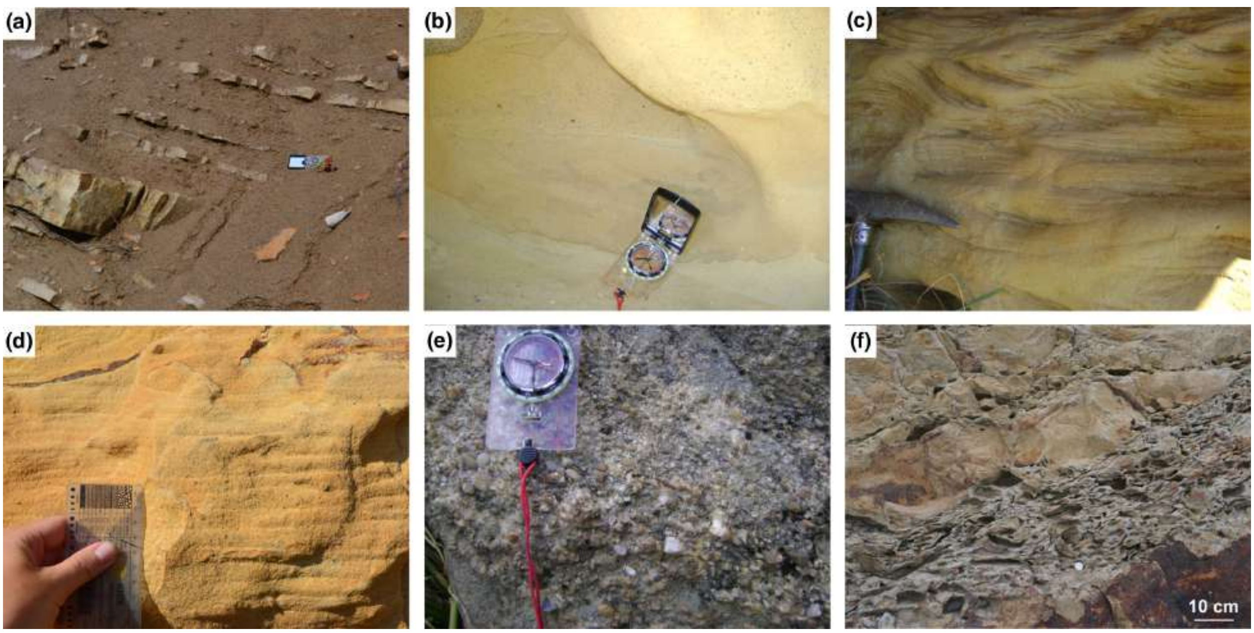



**Fig. 9.** Photos of the representative lithofacies of log MS1. (a) Thin-bedded sandstones and siltstones interbedded with thick sandstone packages; (b) Well-sorted coarse and clean sandstone; (c) Example of convolute lamination found towards the top of a normally graded sandstone bed; (d) Coarse sandstone with parallel lamination; (e) Pebbly conglomerates found towards the top of the Mt. Salici section; (f) Mudclast conglomerates interbedded with coarse sandstones.

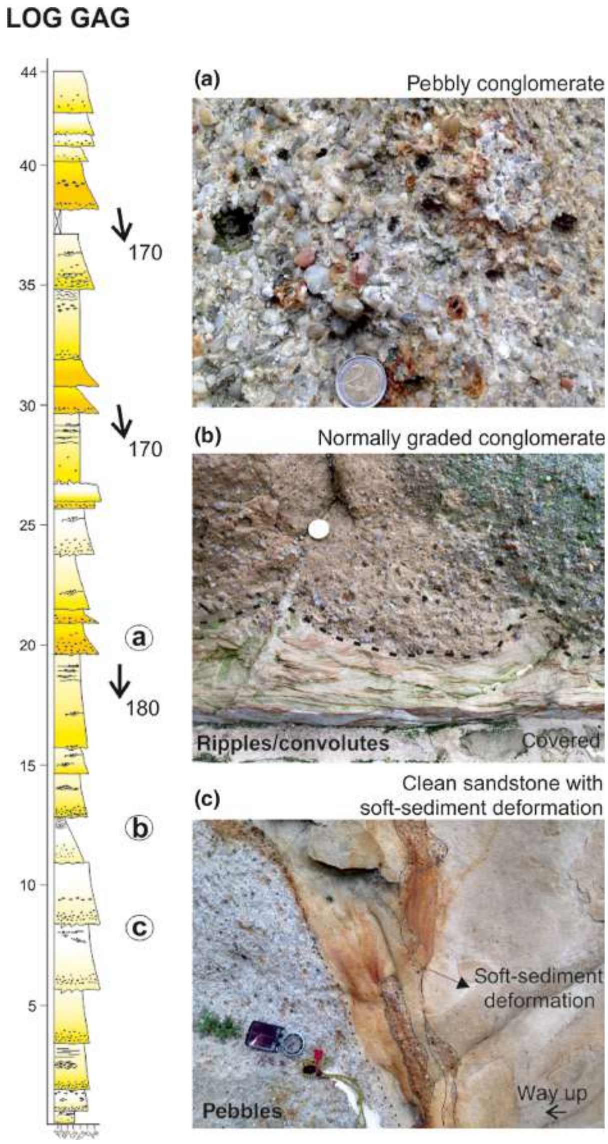



**Fig. 10.** Sedimentary log GAG of the Gagliano castle section and representative photos. (a) Pebbly conglomerates found at most of the bed bases in the Gagliano castle section; (b) Normally graded conglomerates eroding underlying a rippled interval; (c) Contact between pebbly conglomerates and sandstones with evidence of soft-sediment deformation (coarse-grained foundering). Palaeocurrents are presented as arrows along the sedimentary log and their values represent present-day measurements (unrestored rotation).

– individual beds are predominantly ungraded and display an abrupt decrease in grain-size in the top contact.

## Architecture of the Mt. Salici-Gagliano section

The stratigraphy of the Mt. Salici section is dominated by sheet-like architectural elements that occur predominately as amalgamated packages that are laterally extensive (ca. 5 km). Beds are predominantly tabular and the coarser fraction shows a lack of significant incision into underlying deposits. The stratigraphy in the western portion of Mt. Salici section (locality called Pzo. Cardace; Fig. 2a) represents a zone of amalgamation, with a high N/G succession approximately 200–300 m width, composed of lenticular sandstones. There is a gradual grain-size change and decrease in N/G from Pzo. Cardace to the margins (Mt. Salici, Fig. 6a). The sandstone-rich area 4 km wide pinches out laterally (towards NEE) into finer-grained facies. The architecture of the conglomerates at Gagliano castle section is difficult to determine, although a tabular geometry is present at outcrop scale, the lateral continuity cannot be defined precisely due to later deformation. The coarser sediment fraction presumably corresponds to a thalweg position within the fairway. This assumption is based on the geometry of similar facies in the Nebrodi-Madonie district, northern Sicily (Pinter *et al.*, 2016), where coarse facies of Numidian generally form laterally continuous lenses with only limited erosion.

## Sedimentology of Pietra Perciata section

The characterization of the sedimentology of the Pietra Perciata section (Fig. 11) comes from the stratigraphic log collected from the section at south of Catenanuova (Fig. 2a). This comprises 200 m of continuous stratigraphic section from the Dittaino river (477310 m E; 4155449 m N) and passes up to the Serravallian age deposits near Catenanuova. The focus of this study, however, is the first Numidian sandstone bed-set of the sequence, which forms the escarpment of Pietra Perciata. The Numidian sandstone beds dip towards the NNE and the section is approximately perpendicular to the palaeoflow.

The basal part of the Pietra Perciata section displays predominant fine-grained sediments, with rare thin-bedded sandstones and siltstones. The sand content and grain-size increase towards the top of the section. The top of the section (Log PP, Fig. 11) comprises bed-sets of amalgamated sandstones with a conglomeratic base. In general, the sandstone beds are normally graded, well-sorted, from very coarse to fine grain-size (Fig. 11a) with common convolute lamination towards the top (Fig. 11b). Basal contacts are slightly erosive (*ca.* 10 cm). The conglomerates (Fig. 11c) at the base of the sandstone succession (CC in Fig. 7b) are characterized by bed-sets of 4 m, with individual beds of up to 2 m thick. Individual beds show weak normal grading. The conglomerate matrix is composed of quartz granules and pebbles with carbonate clasts and shell fragments (Figs. 11c, d). The carbonate clasts range from 1 cm to cobble size, are sub-angular to sub-rounded (Fig. 11e), and comprised of plastically deformed and moulded, fine-grained carbonate

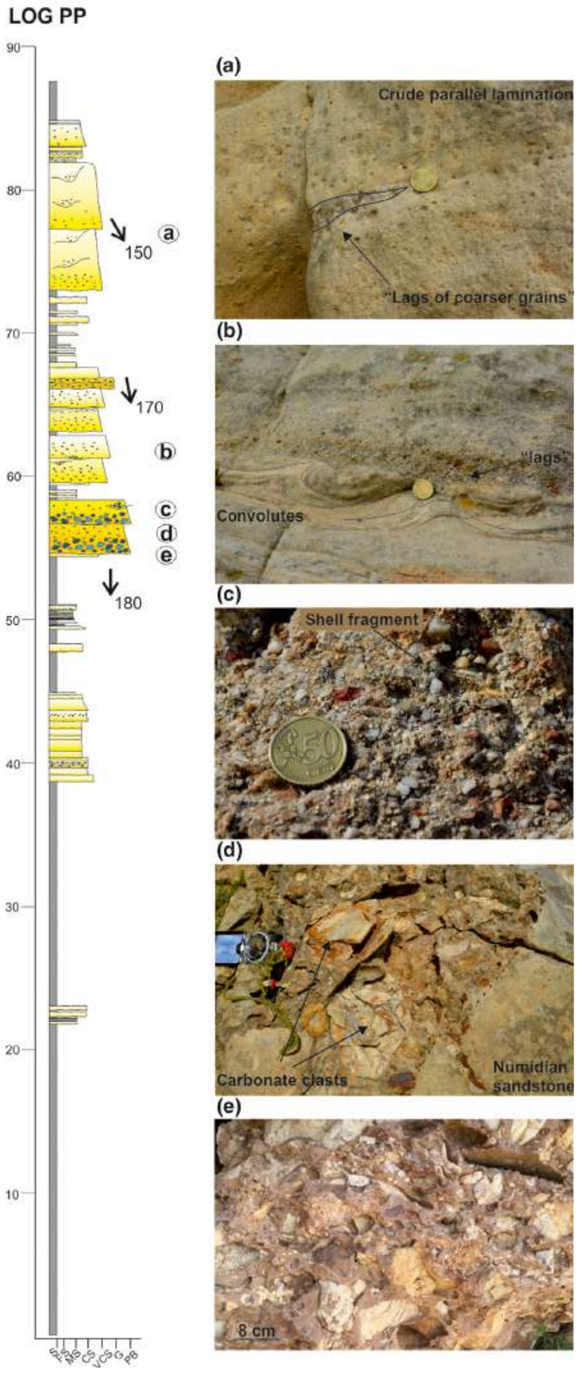



**Fig. 11.** Sedimentary log PP of the Pietra Perciata section (see log location in Fig. 7a) and representative photos. (a) Coarse sandstone with crude parallel lamination and pockets of coarse-grained material (foundering); (b) Normally graded sandstone bed with convolute lamination towards the top; (c) Quarzitic pebbly sandstones with carbonate clasts and shell fragments; (d) Conglomeratic lithofacies with carbonate clasts of cobble sizes; (e) Detail of the conglomerates with abundant carbonate clasts interpreted to be derived from substrate (*Polizzi Formation*). Palaeocurrents are presented as arrows along the sedimentary log and their values represent present-day measurements (unrestored rotation).

mudstones. Primary shell fragments are less frequent, and measure up to 3 cm. Collectively, these carbonate clasts, which are highly atypical of the Numidian system, being restricted to the coarse deposits at Pietra Perciata. We interpret these clasts as having being sourced from the *Polizzi Formation* (Eocene) that locally forms the substrate to the Numidian in Central Sicily. They have been entrained into the conventional Numidian bed-load of coarse quartz sand and pebbles.

### Architecture of the Pietra Perciata section

The area at South of Pietra Perciata section is deformed by two high-angle thrusts that carry sections of Mesozoic substrate to outcrop. These form the tectonic inliers of Mt. Scalpello and Mt. Judica (Fig. 2b). However, these thrusts do not disrupt the bed-set continuity of the Numidian sandstones around Pietra Perciata – bed-sets can still be traced for over 4–5 km along strike in the hanging-wall to the Mt. Scalpello thrust. Overall, the Numidian sandstones are tabular with localized shallow erosional features (*ca.* 30 cm) forming lenticular sandstone bodies that pinch-out laterally. The conglomeratic interval is slightly incised into the underlying fine-grained deposits and could not be traced laterally.

### Sand body geometries

Sandstone bed-sets at Mt. Salici are generally laterally continuous for *ca.* 5–10 km and form tabular deposits without major incision in the underlying deposits. Thus, we infer that they formed as highly elongate ribbons, rather than distinct channels. The sediment distribution within these ribbons are interpreted to be influenced directly by structures in the substrate, with thicker sections deposited along the main sand-fairways and thinner sections deposited in elevated areas of the basin. In contrast, sandstones in the Pietra Perciata section show limited lateral extent, significantly greater amalgamation and erosion of underlying beds. This contrasts with the tabular bed-sets of Mt. Salici and may be associated with variations in the flow confinement. Tabular sandstones are deposited in a relatively broad and less confined fairway than the more amalgamated sandstones (e.g. McCaffrey *et al.*, 2002).

## DISCUSSION

### Structurally controlled sand-fairways

The main sandstone units of the Numidian megasequence of central Sicily are very high N/G and show abundant evidence for bypass whereby flows carried finer grain-sized fractions (less than medium sand) down-system. The bed-sets are stacked, and can be traced for many km down palaeoflow. However, they appear to be encased in finer-grained deposits. These attributes are consistent with models of confined turbidite deposition. There are no stacked successions of finer sand that might be expected if the system was auto-confined by levees not are the coarse-grained bed-sets deeply incisional. Therefore, we infer that the causative turbidity currents were confined against palaeo-slopes that defined long, narrow corridors. These corridors presumably opened down-system – for if they closed up within central Sicily the causative turbidity currents would have been ponded and back-reflected off retaining palaeo-slopes. Here, we infer that the variable sediment distribution and styles are related to structures developed on the basin-floor which routed sand-fairways through different areas at different times in the basin. This could be associated with both inherited and active intra-basinal topography during the Numidian deposition, or with differential basin subsidence. Although we cannot demonstrate the exact nature of the basin-floor structures in the Numidian basin, it is highly probable that these were thrust controlled, as they were in northern Sicily (Pinter *et al.*, 2016). The direction of sediment routing is essentially parallel to the trend of thrust-related basins that controlled deposition of the younger Miocene deposits on Sicily (e.g. Butler & Grasso, 1993). Long-active thrust structures are reported elsewhere in Sicily (Butler & Lickorish, 1997). Thus, although we cannot eliminate definitively that syn-Numidian basin-floor topography may have had other origins (inherited, other structural explanations), the suggestion of active thrusting controlling sediment routing appears the least astonishing explanation. This inference is developed further below.

## Reconstructing fairways in Central-East Sicily

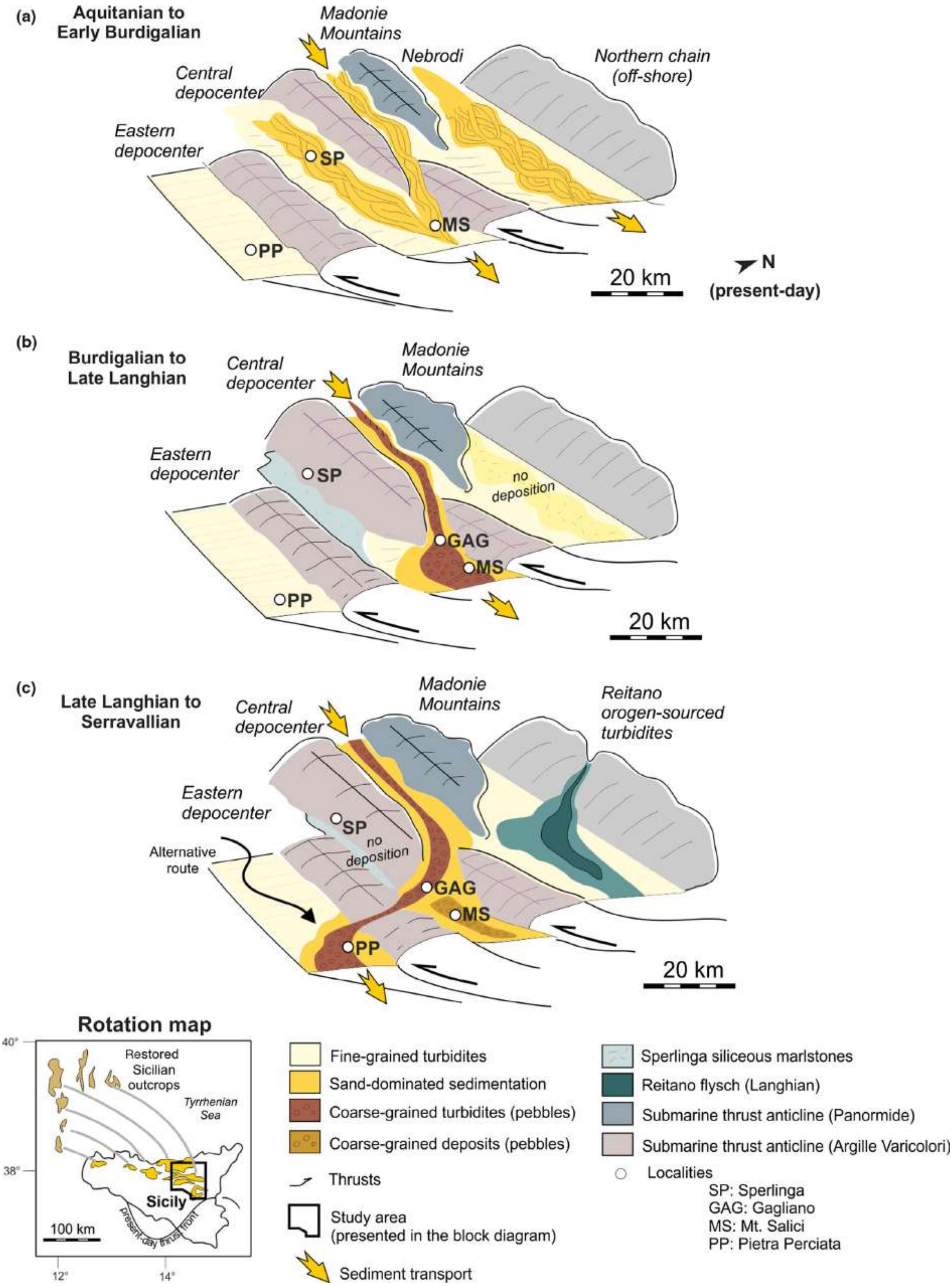
Using the approach of tracking coarse sandstones to identify the main sand-fairways in the basin, we integrate the thickness of the successions, the grain-size dispersal pattern and the age to reconstruct the evolution of the Numidian depocentres in Central-East Sicily. Both the Mt Salici and Sperlinga sections display stacked and amalgamated coarse-grained sandstones up to Burdigalian times, presumably deposited along a sand-fairway (Fig. 12a). However, Mt. Salici section records a consistent coarsening upwards trend until Langhian times while in Sperlinga the sedimentation of the siliceous marlstones prevailed during the mid-Burdigalian. Thus, by Langhian times the Sperlinga area had stopped receiving coarse-grained sand and became 'sediment-starved', isolated from any sand-fairway. However, the coarse sand continued to reach, and bypass through Mt. Salici. While Mt. Salici was predominantly receiving coarse sand, the area downstream (Pietra Perciata) was dominated by fine-grained turbidites (Fig. 12b). The Pietra Perciata section began to receive coarse-grained sedimentation during early Langhian. During this time, turbidity currents breached the anticline formed between Mt. Salici and Pietra Perciata depocentres, and deposited the basal sandstone with the 'reworked substrate conglomerates' including carbonate clasts sourced from the *Polizzi Formation* (Fig. 12c). To date, these are the youngest coarse Numidian clastics in northern and Central Sicily and presumably represent the terminal sand-fairway for the system.

## Extending the confined turbidite model

Pinter *et al.* (2016) showed that the Numidian facies schemes proposed by the previous authors (Carbone & Grasso, 2012; Servizio Geologico d'Italia, 2012) for the Nebrodi-Madonie area are lateral equivalents and interpreted the abrupt facies changes (over a few km) as a result of turbidity current deposition controlled by palaeo-slopes and intra-basin topography. Although the Numidian megasequence of Central-East Sicily is regarded as occurring in a more structurally disrupted part of the system, similar thickness and facies variations are observed in the sections, presumably being result of turbidity current interaction with basin-floor thrust structures progressively developed in response to the compressional regime of the advancing Maghrebian orogen. These short-range lateral facies and thickness changes are classically related to deposits of thrust-top basins (Morley & Leong, 2008), with growth sequences related to substrate deformation (e.g. development of thrust folds).

Prior to our study, both in Central-East Sicily outlined here and in the Nebrodi-Madonie area to the North

**Fig. 12.** 'Connected tortuous corridors' model for the Numidian of Central-East Sicily. (a) Nebrodi-Madonie area (locality studied by Pinter *et al.*, 2016) and Central Sicily area are dominated by sand sedimentation from late Aquitanian to early Burdigalian times, with only fine-grained sediments reaching the Eastern area of Pietra Perciata; (b) Towards the Burdigalian to late Langhian, the Sperlinga sand-fairway is off and the Central area of Mt. Salici/Gagliano starts receiving coarse sedimentation through tortuous corridors of coarse-grained sediments that breached across the northern anticline; (c) At late Langhian to early Serravallian, the sand and coarse-grained sedimentation breach across the southern anticline and reach the eastern area of Pietra Perciata. We interpret that the mudclast conglomerates at Mt. Salici section and the conglomerates composed of the reworked substrate material found at the base of the Pietra Perciata section are product of erosion of the anticlines that evolved and separated these areas (synclines) in distinct Numidian depocentres.


(a)
Aquitanian to Early Burdigalian
Madonie Mountains
Nebrodi
Northern chain (off-shore)
Central depocenter
Eastern depocenter
SP
MS
PP
20 km
N (present-day)
(b)
Burdigalian to Late Langhian
Central depocenter
Madonie Mountains
Eastern depocenter
SP
no deposition
GAG
MS
PP
20 km
(c)
Late Langhian to Serravallian
Central depocenter
Madonie Mountains
Reitano orogen-sourced turbidites
Eastern depocenter
SP
no deposition
Alternative route
GAG
MS
PP
20 km
Rotation map
40°
38°
12°
14°
Restored Sicilian outcrops
Tyrrhenian Sea
Sicily
present-day thrust front
100 km
Fine-grained turbidites
Sand-dominated sedimentation
Coarse-grained turbidites (pebbles)
Coarse-grained deposits (pebbles)
Thrusts
Study area (presented in the block diagram)
Sediment transport
Sperlinga siliceous marlstones
Reitano flysch (Langhian)
Submarine thrust anticline (Panormide)
Submarine thrust anticline (Argille Varicolori)
Localities
SP: Sperlinga
GAG: Gagliano
MS: Mt. Salici
PP: Pietra Perciata

(Pinter *et al.*, 2016), the Numidian system had been interpreted as being deposited in unconfined fans (Giunta, 1985; Guerrera *et al.*, 2012 and references therein). In this previous model, different outcrops containing different facies were considered to have come from geographically distinct, and widely separated parts of the ancestral Numidian basin. The present-day close proximity of distinct facies had been generally ascribed to large-displacement thrusts (Bianchi *et al.*, 1987; Carbone *et al.*, 1990; Lentini *et al.*, 1996; Bello *et al.*, 2000). However, our work in both Nebrodi-Madonie and Central-East Sicily indicates that the short-range facies variations within the Numidian succession are associated to syn-tectonic deposition of turbidity currents upon a complex basin-floor rather than being result of exclusive post-depositional deformation.

## APPLICATIONS AS AN ANALOGUE

From a subsurface perspective, the Numidian of Central-East Sicily is a good system to evaluate the impact of basin-floor structures on turbidity current deposition. Although the system contains widespread, thick, clean and coarse-grained sandstones, these high-quality reservoir analogues may be focussed through narrow, elongate conduits. The Numidian megasequence is characterized by thin ribbon sand-fairways rather than sheets that span across thrust-sheets. While this increases depositional thickness and sand quality locally, it makes targeting strips of high-quality reservoir much harder – as many parts of the system will lie off-fairway and are less sand-prone. This raises issues in terms of understanding hydrocarbon reservoir distribution in the subsurface, not only in other parts of Sicily but also in equivalent tectonic settings such as the southern Caribbean (e.g. Deville *et al.*, 2015) and Nankai though (e.g. Pickering *et al.*, 1993). In these settings, where deformation continued after deposition of the reservoir units, uncertainties in structural geometry may already carry substantial risk. The addition of complex sand geometries, which arise from connected ribbon-like fairways rather than lateral extensive sheets, may impact critically on exploration and development decisions. Conversely, the confined turbidite systems that are routed through structurally controlled corridors may offer the potential to find high-quality sand deposited down-system, opening further exploration opportunities.

## CONCLUSIONS

The observations presented here for Central-East Sicily are inconsistent with the extant model for Numidian deposition occurring as an unconfined turbidite system. They are consistent with our earlier study in Northern Sicily (Pinter *et al.*, 2016) that Numidian sandstones accumulated along tortuous corridors and thus the system was structurally confined. It is the continuous development of these structures that subsequently disrupted the original basin arrays within which the Numidian succession accumulated. The presence of deforming substrate can be directly inferred from short-range facies and thickness variations. The structural controls on sedimentation are observed at the scale of growth sequences and at bed scale with basis on key-sedimentological features (e.g. abrupt tops that indicate bypass sediments). The overall configuration of the inferred substrate relief at the time of deposition is characterized by interconnected depocentres that evolved through time from late Aquitanian to early Serravallian. This configuration is similar to the 'connected tortuous corridors' basin fills described by Smith (2004). This new insight into the tectonic evolution of the Numidian of Central-East Sicily as a syn-orogenic turbidite system challenges the previous tectonic models and highlights further questions on the evolution of the Numidian system itself and in the understanding of the Central Mediterranean systems. We will address how understanding of the Numidian depositional system can give new insights on the central Mediterranean palaeogeography during Early-Middle Miocene times in subsequent papers. Additionally, this system highlights exploration risks in analogous tectono-sedimentary systems, such as the southern Caribbean. This study demonstrates that it is possible to extend understanding of turbidites into more deformed settings and that these endeavours are important for increasing large-scale understanding of ancient depositional systems.

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## SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

**Appendix S1.** Sample location and main calcareous planktonic species recognised in the studied sections.

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