JOURNAL OF THE GEOLOGICAL SOCIETY PROOFS

Article DOI: 10.1144/jgs2020-008

Article number: jgs2020-008

When citing this article please include the DOI provided above.

Instructions

1. **We need to clearly see the changes you have made.**
   Do: annotate PDF using the comment facility, or provide a separate list of your corrections using line numbers.
   Don't: send a revised word file of your manuscript or internally edit the PDF. Help on making proof corrections is available at http://www.geolsoc.org.uk/ProofCorrections
2. **Proofs (typeset version) should not be posted to any website or server.** You can post the accepted (pre-typeset) manuscript 12 months after online publication or the original (i.e. not peer reviewed) manuscript now. These proofs are for checking purposes only. They should not be considered as final publication format and must not be used for any other purpose. Please do not print and distribute multiple copies. Neither excerpts nor the article in its entirety should be included in other publications until the final version has been published and citation details are available. Please see our Terms and Conditions at https://www.geolsoc.org.uk/Publications/Lyell-Collection/Using-the-Lyell-Collection/Copyright-Permissions-and-Terms-of-Use/Copyright-Policy-and-Terms-of-Use-for-Authors
3. **Permissions:** Permission to reproduce any third-party material in your paper should have been obtained prior to acceptance. If your paper contains figures, tables or text requiring permission to reproduce, and you have not already obtained that permission, please inform me immediately by email.
4. **Check this proof carefully for errors:** Once it is published online no further changes can be made.
5. **Figures and tables:** Please check that they are complete and the correct content and legend are present. Figures in the proof are low-resolution versions that will be replaced with higher resolution versions when the paper is published. If you need to replace/resupply any figures, please indicate this in your proof amends and upload them to the following ftp site:

   Site Name: ftp.novatechset.com

   username: gsl_guest

   Password: Gst!@#090418

   If you have FTP software (such as Filezilla) you can place the figures directly onto the FTP site detailed above. If you do not have FTP software, a free version of Filezilla can be downloaded from here: https://filezilla-project.org/. Or, you can send your figures to your GSL Production Editor (reply to your proof email) and they will upload the figures on your behalf.
6. **Special characters:** Please check that special characters, equations, taxonomy and units, if applicable, have been reproduced accurately.
7. **ORCID IDs:** Only those supplied at submission stage appear on this proof. Additional ORCID IDs can be added as part of your corrections.

Funding information

- Only funding information supplied at submission (shown in the table below) will be transmitted to CrossRef, assuming the mandatory fields are complete. Please provide additional information in the table below if required.
- Instructions on how to add missing or additional funding information can be found at http://www.geolsoc.org.uk/ProofCorrections
- Please note that providing additional funding information does not alter the text in the Funding section of your proof. If you have any changes to this section, please provide as part of your corrections.

Funding agency (mandatory)	**Funding agency ID (mandatory)**	**Grant number (optional)**	**Principal award recipient**
Shell United Kingdom (GB)	Author to provide ID	not applicable	Not Applicable
CNPq	Author to provide ID	Patricia Pinter	
University of catania	Author to provide ID	not applicable	Rosanna Maniscalco

Please answer all queries

No	**Query**
1	Please check this proof carefully for errors; once it is published online no further changes can be made. In particular, check author names, affiliations & corresponding e-mail address, and that figures are correct
2	Reference Critelli et al. (2018) does not appear in the reference list. Please provide full publication details or delete all citations.
3	Reference von Hinsbergen *et al.* (2019) does not appear in the reference list. Please provide full publication details or delete the citation.
4	Reference Speranza *et al.* (2012) does not appear in the reference list. Please provide full publication details or delete the citation.
5	Reference Dewever *et al.* (2010) does not appear in the reference list. Please provide full publication details or delete the citation.
6	Reference Lentini & Carbone (2012) does not appear in the reference list. Please provide full publication details or delete the citation.
7	Reference De Capoa *et al.* (2012) does not appear in the reference list. Please provide full publication details or delete the citation.

8	Please note that the reference citation Bianchi *et al*. (1989) has been changed to Bianchi *et al*. (1987) as per the reference list. Please confirm this is correct.
9	Reference Carbone *et al*. (1987) does not appear in the reference list. Please provide full publication details or delete the citation.
10	Please note that the reference citation Breton *et al*. (2017) has been changed to Le Breton *et al*. (2017) as per the reference list. Please confirm this is correct.
11	Reference Stephenson *et al*. (2015) does not appear in the reference list. Please provide full publication details or delete the citation.
12	In Funding section, please add grant numbers
13	Reference "Accaino *et al.* 2011" is not cited in the text. Please cite or delete it.
14	Reference "Balogh *et al.* 2001" is not cited in the text. Please cite or delete it.
15	Reference "Cassola *et al.* 1992" is not cited in the text. Please cite or delete it.
16	Reference "Cassola *et al.* 1995" is not cited in the text. Please cite or delete it.
17	Reference "Civile *et al.* 2016" is not cited in the text. Please cite or delete it.
18	Reference "Critelli 1991" is not cited in the text. Please cite or delete it.
19	Reference "de Capoa *et al.* 2000" is not cited in the text. Please cite or delete it.
20	Reference "de Capoa *et al.* 2002" is not cited in the text. Please cite or delete it.
21	Reference "de Capoa *et al.* 2004" is not cited in the text. Please cite or delete it.
22	Patacci et al. 2020 - please update if possible (volume number, page numbers of paper)
23	Reference "Pedley 1981" is not cited in the text. Please cite or delete it.
24	Fig. 2 - if any figures have been reproduced from elsewhere please obtain permission from original publisher and add suitable acknowledgement to caption/s
25	Fig. 2 caption - reference Meulenkamp *et al*. (2003) does not appear in the reference list. Please provide full publication details or delete the citation.
26	Fig. 11 caption - please confirm change to ‘left’ is correct

JGS
Research article
Journal of the Geological Society
Published Online First
https://doi.org/10.1144/jgs2020-008

Q1

Deep-water sand-fairway mapping as a tool for tectonic restoration: decoding Miocene central Mediterranean palaeogeography using the Numidian turbidites of southern Italy

Robert W.H. Butler[1], **Patricia R. Pinter**[1,2], **Rosanna Maniscalco**[3] **and Adrian J. Hartley**[1]

[1] School of Geosciences, University of Aberdeen, Aberdeen AB24 3UE, UK
[2] Present address: PRP, CGG Services (UK) Ltd, Tyn Y Coed, Llandudno LL30 1SA, UK
[3] Department of Biological, Geological and Environmental Sciences, University of Catania, Corso Italia, 57, 95129 Catania, Italy
RWHB, 0000-0002-7732-9686; RM, 0000-0003-1026-044X; AJH, 0000-0002-5799-4734
* Correspondence: rob.butler@abdn.ac.uk

Abstract: As turbidity currents are sensitive to the geometry of the substrate across which they flow, the sedimentology of turbidites can chart the development of submarine structures and reveal regional palaeobathymetric connections. This rationale is applied to understand the tectonic evolution of the central Mediterranean in the early Miocene, using the African-sourced, hyper-mature Numidian sandstones and their immature, orogen-derived time-equivalents. In both Sicily and the southern Apennines, the Numidian sequence displays characteristics of confined–uncontained turbidites: grain-size breaks and coarse bedload indicative of ubiquitous flow bypass; short-range grain-size fractionation across flow; stacked sandy bed-sets in the flow axes. We reconstruct sand fairways for over 300 km across the region and propose that their causative flows, axially fed from north Africa, were confined along sinuous corridors created by active submarine thrusting. In contrast, orogen-derived turbidites (e.g. Reitano flysch, confined–contained turbidites) were ponded in mini-basins higher on the thrust wedge. The composite Apennine–Calabrian–Maghrebian orogen with its submarine thrust belt had occluded deep-water Tethyan connections through the central Mediterranean by early Miocene times. Palaeobathymetry across the submarine thrust belt increased northwards into the future Apennines. This study illustrates the utility of turbidite sedimentology, especially reconstructing sand fairways, in building palaeogeographical reconstructions of complex tectonic regimes.

Received 14 January 2020; **revised** 29 February 2020; **accepted** 3 March 2020

This paper aims to illustrate how the sedimentology of sandy turbidites can inform palaeogeographical reconstructions in tectonically complex regions. The relative positions of the plate interiors and the major continental blocks are well constrained globally, certainly for the Mesozoic to present day (e.g. Müller *et al.* 2016). Interpretations of the tectonic evolution of these regions are commonly illustrated on time-series of palaeogeographical maps that display transient arrangements of continental fragments, oceans and sedimentary basins (e.g. Stampfli and Borel 2002; van Hinsbergen *et al.* 2020). These in turn can underpin 3D models of plate interactions and associated geodynamic processes such as rates of slab roll-back (e.g. Lucente *et al.* 2006). They are also used to erect models of past oceanographic circulation and as inputs to climate models. However, constraining the positions of smaller blocks and basins within complex areas of plate convergence, such as in SE Asia (e.g. von Hagke *et al.* 2016), the southern Caribbean (e.g. Meschede and Frische 1998) and in the western Tethyan regions (e.g. Le Breton *et al.* 2017), is far less certain. Testing the variety of different palaeogeographical reconstructions, and choosing between alternatives, necessarily involves adding new data and syntheses. Here we use a case study from the central Mediterranean during the early–middle Miocene, building upon exceptional studies of sandstone provenance (e.g. Thomas *et al.* 2010; Q2 Fornelli *et al.* 2015, 2019; Critelli *et al.* 2017, 2018). In doing so, we bridge the scale gap between outcrop and plate configurations by integrating observations and interpretations from several field studies. New insights arise from applying concepts developed in recent years on the deep-water sedimentology, especially concerning structurally confined turbidity currents.

As examples of subaqueous gravity flows, turbidity currents seek bathymetric lows. Therefore, tracking their pathways provides powerful constraints, not only on the relative bathymetry of their substrate but also on the bathymetric relief (structure) of the pathways they follow. In this paper, we use the Numidian deep-water sandstones and associated deposits that are preserved in Sicily and the southern part of peninsular Italy to understand relationships between the southern Apennines and eastern Maghrebian orogenic belts, which now host these strata. Our aim is not only to revise palaeogeographical restorations of the central Mediterranean during the Miocene but also to provide a rationale for the general application of stratigraphic and sedimentological methods applied to deep-water deposits in the study of orogens and their associated basins.

Syntectonic turbidites have been widely used to calibrate palaeogeographical reconstructions; for example, in dating collision between India and Asia (e.g. Rowley 1996; Hu *et al.* 2016). These studies have used classical approaches, treating the deposits as blankets that seal tectonostratigraphic units and establish the timing of their juxtaposition. Alternatively, turbidite provenance has been used to inform the proximity between land-masses at the time of deposition and thus date impending collision (e.g. Hu *et al.* 2016), including in the central Mediterranean (e.g. Critelli *et al.* 2017). However, substantial further information can be gleaned from the sedimentology of turbidites, and deductions of the deep-water sediment processes derived from these studies. Advances in understanding turbidites have accelerated in the past decade: by deducing sediment processes, we are able to infer the character of the pathways along which the causative turbidity currents flowed. These deductions can be used to identify the location, amplitude and continuity of structures in the syndepositional seabed and in turn, inform palaeogeographical models.

Significant insights on the scale of deepwater depositional systems, their depositional architectures and relationships to evolving seabed structures have come from modern systems, using both high-resolution bathymetric maps and 3D seismic volumes. In ancient, deformed basin systems that inform palaeogeographical reconstructions of tectonically complex regions such as the central Mediterranean, seismic-scale features are only rarely preserved or recognized. Consequently, it is the outcrop-scale sedimentology that yields the critical information, equivalent to utilizing well penetrations without seismic data for investigations in modern examples. Despite this limitation, we aim to show that significant insights are still possible.

This paper first outlines the key sedimentological elements of deep-water turbidites before introducing the tectonic setting of our case study in the central Mediterranean (Miocene). We then focus on the sedimentological and stratigraphic data of the Numidian turbidites of Sicily and southern Italy, building a depositional framework that informs discussion of palaeogeographical reconstructions in the region. This case study illustrates the general approach we take and that could be applied elsewhere.

Confined turbidite systems: a brief introduction

Concepts of turbidite sedimentology have been developed over many decades (e.g. Mutti 1992; Meiburg and Kneller 2010, and references therein). Our challenge is to use turbidite deposits and their inferred transport processes to deduce the morphology of their host basins. In the following section (Fig. 1) we use the terminology and approach of Southern *et al.* (2015), who classified the shapes of basin morphology, their controls on turbidite systems and resultant facies distributions.

Traditional understanding of turbidite systems, as typically reported in textbooks and reviews (e.g. Mutti and Ricci Lucchi 1978; Reading and Richards 1994; Stow and Mayall 2000; Pickering and Hiscott 2016; amongst many others), uses concepts largely dating from what Shanmugam (2016) termed the 'heydays of submarine fan models' (1970s–1980s). In these models, sediment volumes build out onto open, laterally continuous basin plains. These unconfined turbidite systems (Fig. 1a) characterize some of the largest depositional bodies on Earth. Modern examples include the mega-fans that are building into ocean basins (e.g. Niger, Indus, Ganges–Brahmaputra, Amazon). Large flows in large basins generate deposits across which lateral facies variations occur over long distances. These systems can have locally auto-confined flows, within submarine channel systems that build levees. Classical descriptions argue that outside these channels, flows are free to expand and wane and the reduction in the capacity of flows to carry grains generates simple fining-upwards beds that are characteristic of the classical so-called Bouma sequence (e.g. Bouma 1962; Bouma and Ravenne 2004; Fig. 1a). Recent work has suggested that flow transformations can generate facies changes over short

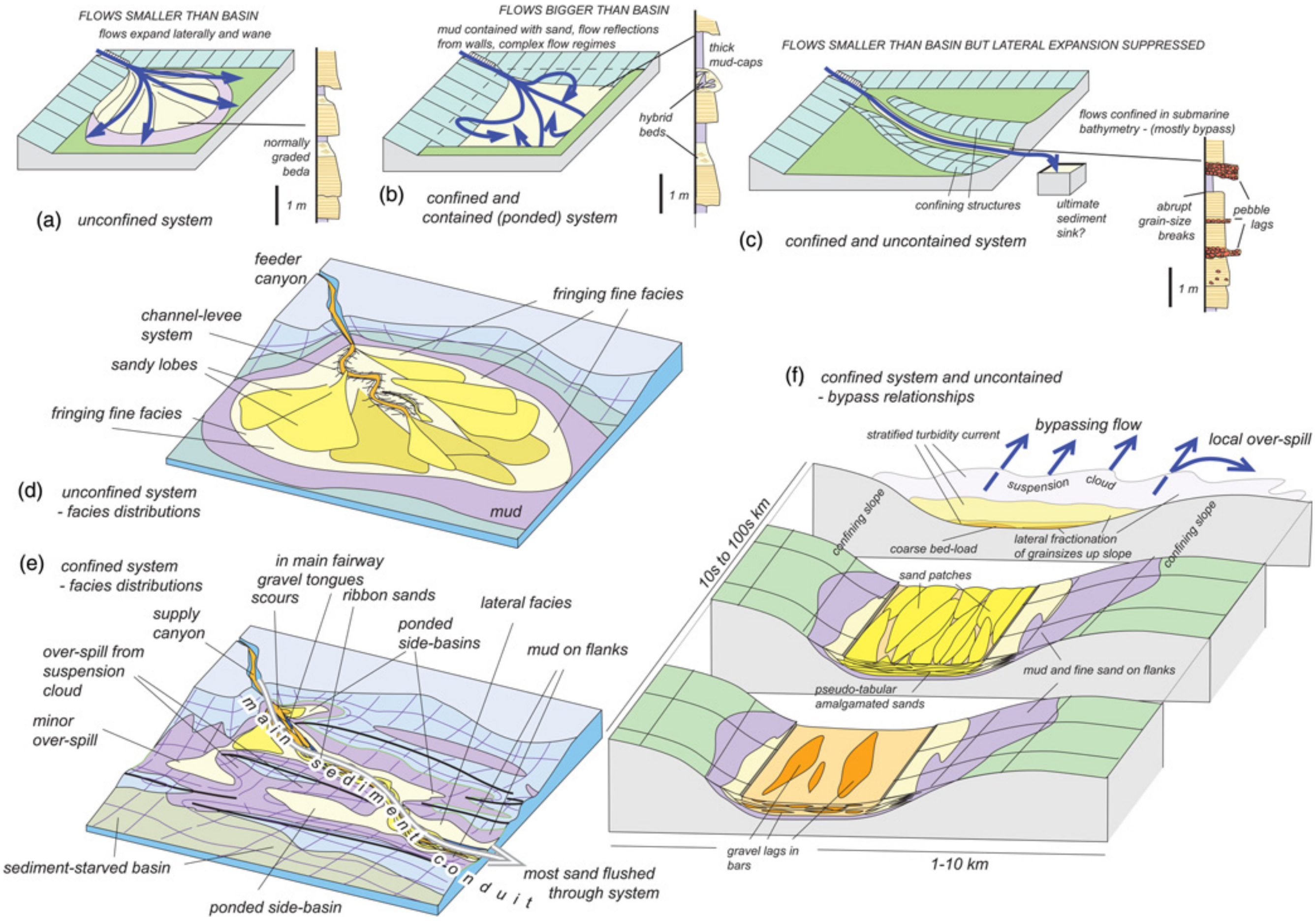

Fig. 1. A compilation of turbidite sedimentology, for sandy siliciclastic systems. Flow routing is shown by blue arrows. (**a**–**c**) Definitions of turbidite systems with some diagnostic facies. (**a**) An unconfined system, characterized by fining-upwards deposits. (**b**) A confined and contained (ponded) system with the integration of mud, both as thick bed caps and within complex 'hybrid' beds within the sand. (**c**) A confined but uncontained system where coarse-grained fairway of sand and gravel indicative of flow bypass is fractionated from the finer grains. (**d**) The distribution of facies on an unconfined fan; contrasted with facies distributions on a structurally confined but uncontained system (**e**). (**f**) The relationship between facies within a confined, uncontained sand fairway and the marginal facies along a structured corridor.

distances (e.g. Kane *et al.* 2017). Nevertheless, unconfined systems tend to build sediment bodies that broadly fine outwards, away from the fan apex. Fine-grained facies fringe the fans with coarser sands closer to the fan apex and its distributor fan-top channels (Fig. 1d).

A contrasting scenario exists where turbidity currents are restricted laterally by confining slopes so that they flow along structurally controlled corridors. These are confined systems (in the sense of Southern *et al.* 2015: Fig. 1b and c). It should be noted that the distinction between unconfined and confined turbidites relates the size of the causative flow to the size of the basin into which they flowed. It is probable that many ancient outcropping turbidite systems that have been studied, certainly in syn-orogenic and other active basin settings, are confined by the architecture of their host basin. Southern *et al.* (2015) divided confined systems into contained (ponded) or uncontained (Fig. 1b and c).

Mutti *et al.* (2009, p. 305) argued that, until their review, 'studies have shown the importance of structurally induced submarine topography in controlling facies distribution patterns', noting that investigating these interactions would require 'close cooperation between stratigraphers, sedimentologists and structural geologists'. Although, at their time of writing, few such multidisciplinary studies had been attempted (indeed Mutti *et al.* were sceptical that such co-operation would ever happen), there has since been substantial work on confined turbidites. Much of this effort has been directed at forecasting sandstone distribution as possible hydrocarbon reservoirs in the subsurface, by using combinations of scaled analogue and numerical experiments (e.g. Albertão *et al.* 2015; de Leeuw *et al.* 2018), observations and measurements from active natural systems (e.g. Gamberi and Rovere 2011; Stevenson *et al.* 2013) and studies of outcrops of ancient deposits (e.g. Southern *et al.* 2015; Liu *et al.* 2018). In uncontained confined systems, turbidity currents tend to flush down sinuous corridors (Fig. 1e). In this regard, flows tend to overrun significant parts of their confining conduit without leaving deposits, a process generally termed flow bypass.

Building on pioneering studies such as that by Kneller and McCaffrey (2003), Stevenson *et al.* (2015) described the critical sedimentological observations needed to establish flow bypass, the transit of turbidity currents after the partial deposition of some of its sediment content. These include abrupt grain-size breaks in vertical sections that imply flows only dropping coarse parts of their sediment load, with the remaining finer grained fractions continuing down-system (Fig. 1c). Other deposit characteristics include coarse-grained lags of granule- and pebble-grade clasts at the base of beds. These form by the reworking of bed-loads by multiple flow-events without being buried by fallout from the overriding suspension cloud. Isolated pebbles in sandstones are here interpreted as clasts that were stripped out from lags, entrained as saltating outsized grains towards the base of the turbidity current (including within plugs of coarse clasts constituting traction carpets, in the sense of Mutti 1992; Sohn 1997) and then dropped out downstream onto aggrading sand left by a weakly waning flow. These features are generally common in confined turbidites where individual flows can experience complex velocity variations and interaction with submarine structures (created by not only submarine channels but also the margins of basins). The various combinations of different spatial and temporal accelerations produce markedly different vertical and lateral variations in the resulting turbidite deposit.

Experiments, with reference to channel–levee complexes (de Leeuw *et al.* 2018), show that confined turbulent flows develop vertical fractionation of grain sizes. The lower part of the flow is represented by a fast-moving, high-concentration component with increasingly dilute, finer-grained and slower-moving components above. Deposition from these flow components creates coarser, sand tracts in the channel base and builds finer-grained levees on the flanks. Levees aggrade by flows overtopping them and waning away onto the unconfined slopes beyond. For flows that are fully confined by structured bathymetry, the grain sizes equivalent to levees will accumulate up the confining slopes, or be flushed through the system. The coarse sand components will accumulate along the axis of the conduit. Finer-grained deposits, falling out from higher in the turbidity current, tend to accumulate higher on the flanks of the confining bathymetry (Fig. 1f). The result is that turbidite facies can vary over short distances (hundreds of metres) when compared laterally, across the flow direction.

Turbidite sand fairways are the geological record of preferential pathways of confined flows. Their deposits are characterized by clean, coarse-grained sandstones (e.g. Joseph and Lomas 2004) with common parallel lamination indicative of aggradation as the residual flow continues to pass. Abrupt bed tops with grain-size breaks are indicative of bypassed fine-grained fractions (e.g. Kneller and McCaffrey 2003). Here we consider the grain size of sandstones containing primary bed forms such as parallel lamination to be representative of the maximum available grain size that could be carried by turbulent suspension at that point in the causative flow. Larger clasts were therefore presumably carried as dense bed-load and transported at a slower velocity than that of the turbulent suspension cloud, as a traction carpet (in the sense of Mutti 1992; Sohn 1997). The presence of coarser sediment (very coarse sand, granules, pebbles, etc.) in deposits far down-system presumably requires that they have been carried by multiple flows. Most critically, the occurrence of pebbles originating from the original source area in distal deposits requires the upstream regions across which the turbidity currents passed to have been confined so that their capacity to carry coarse sediment was retained. The high-concentration components of the flows should hug bathymetry, moving continuously downslope along the basin fairways. Therefore, it is the distribution of coarse sandstone fractions across a depositional system that is the most informative of the relative bathymetric variations within a basin.

Contained (ponded) systems retain the entire grain-size range carried by the turbidity current (Fig. 1b) including the mud, silt and very fine sand along with coarser fractions. Individual flows therefore leave beds with muddy and silty caps as the suspension cloud is trapped into the basin (e.g. Patacci *et al.* 2015, 2020). Southern *et al.* (2015) noted that this tendency increases the opportunities for subsequent flows to entrain mud. This can change flow dynamics, increasing the propensity of forming so-called hybrid beds (Haughton *et al.* 2009; Baas *et al.* 2011) where clean sands, deposited from turbulent suspension clouds, are interleaved with muddy debrites that record cohesive flow mechanisms.

A challenge in understanding ancient turbidite systems is to track clast provenance. When energetic enough, turbidity currents can erode the substrate across which they transit. The entrained clasts contaminate the resultant deposit and can confuse interpretation of sediment source and basin morphology. The problem is avoided if the turbidites of interest are composed of sands rather distinct from the substrate; for example, quartz-rich turbidity currents routed and deposited upon substrates exclusively composed of carbonates. In orogenic systems, it may be that such turbidites will be the first to enter an otherwise sediment-starved deep-water basin system just as that basin is beginning to be deformed by the orogen. This is the ideal scenario in which to use turbidites to decode the basin geometry.

Geological setting of the Numidian system

To illustrate how the concepts from sedimentary geology outlined above can inform tectonic studies, we use the Numidian (Miocene) turbidite system of Italy. These rocks are found through Sicily and the southern Apennines (Wezel 1970; Critelli 1999, 2018; Guerrera *et al.* 2005, 2012; Fig. 2), incorporated into the eastern Maghrebian

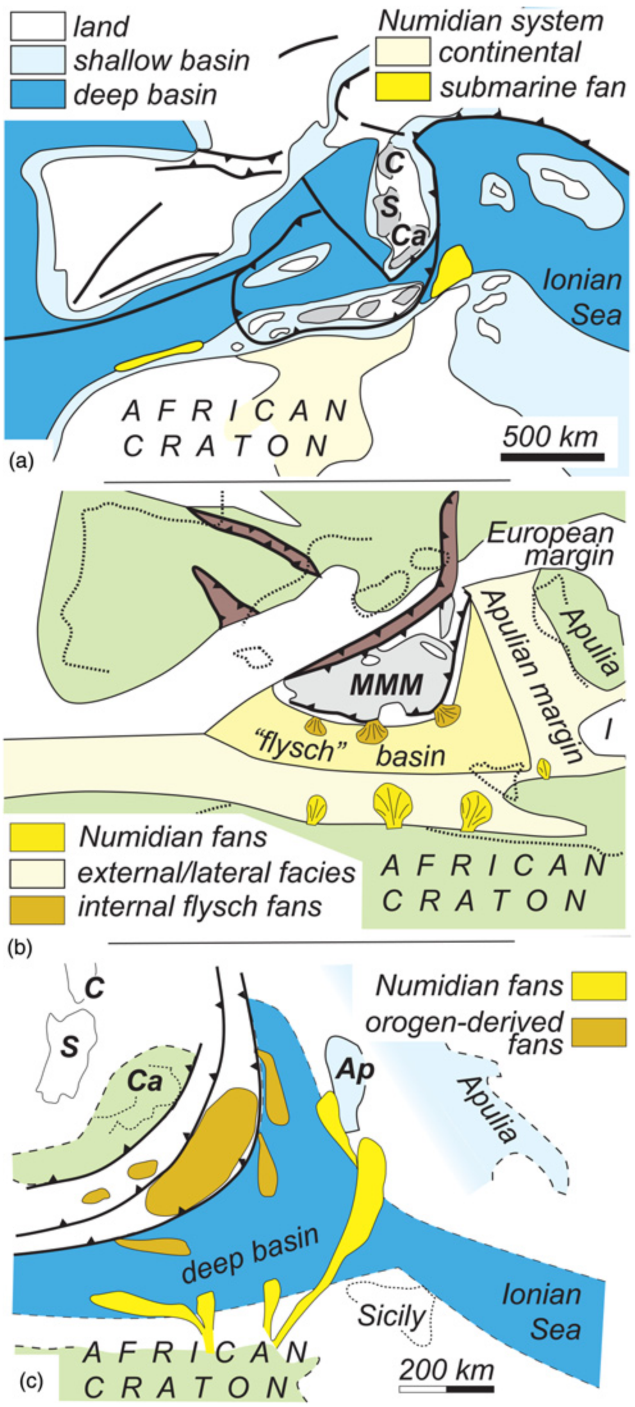

Fig. 2. A compilation of palaeogeographical models for the early Miocene in the central Mediterranean. (**a**) Depiction of the Numidian in Burdigalian times, forming a single unconfined fan opening into a large seaway (from Thomas *et al.* (2010), modified after Meulenkamp *et al.* (2003)). (**b**) Representation of the Numidian and associated turbidite systems in the early Miocene, fed by fans that are significantly smaller than the size of the composite basin (from Guerrera *et al.* (2012)). It should be noted that the fans shown crossing Sicily (and to its east) are incompatible with the geological record (no source area, as discussed in text), and this is corrected by the model of Critelli *et al.* (2017; (**c**)). (**c**) Critelli *et al.* showed the Numidian system for the Langhian forming a narrow depositional tract, ahead of the active orogenic front, and sourced from the African margin to the SW of modern Sicily. C, Corsica; S, Sardinia; Ca, Calabria; Ap, Apennine platform; I, Ionian Sea; MMM, 'Meso-Mediterranean microplate'.

chain, part of the Alpine orogeny, which was developed by convergence between the African and Eurasian continents from the late Mesozoic into the Cenozoic (e.g. Elter *et al.* 2003). The region is a complex collage of continental blocks and former ocean basins of various ages that are caught between the continental interiors of Africa and Europe. Although the relative motion between these two bounding continents is well established within a globally compatible plate-tectonic reference frame (e.g. Muller *et al.* 2016), there are many competing models for the evolution of blocks and basins between them (e.g. Meulenkamp and Sissingh 2003; Handy *et al.* 2010; Zarcone *et al.* 2010; Guerrera *et al.* 2012; Puglisi 2014; von Hinsbergen *et al.* 2019; and many more).

The early Miocene is generally considered to be a pivotal time for the regional tectonic framework of the ancestral Mediterranean, with significant reorganization of continental blocks (e.g. Corsica and Sardinia), opening of oceanic basins (e.g. Gulf of Lion, Balearic Sea) within the broad area of plate convergence between Africa and Europe, and the initiation of the modern Apennine chain (e.g. Lucente *et al.* 2006; Le Breton *et al.* 2017; and references therein). Different models imply different linkages of ocean basins through the region, a key element of which is the westward extent of oceanic lithosphere now represented by the floor of the deep basin holding the Ionian Sea (Speranza *et al.* 2012). Many palaeogeographical models consider this to be a remnant of a vestigial arm of the Tethyan ocean that once entirely separated north Africa from Apulia and various other micro-continental blocks (e.g. Fig. 2a, modified after Thomas *et al.* 2010; and references therein). For Guerrera *et al.* (2012; Fig. 2b), this inferred corridor became occluded by convergence between a composite continental block (the so-called Mid-Mediterranean 'microplate') and the north African margin, with detritus shed from these blocks forming the fill to a 'flysch basin'.

Turbidites of the Numidian system, part of the flysch basin fill, are composed of generally well-sorted medium to coarse, very mature quartz sandstones. Historically, their provenance has been contested (see Parize *et al.* 1986; Thomas *et al.* 2010). However, petrological studies, including zircon compositions, now clearly indicate that they have been derived from cratonic northern Africa (Fornelli *et al.* 2015, 2019; Critelli *et al.* 2017, 2018). As such, the Numidian system is a prime example of a craton-derived sand system, and its deposits are found widely around the margins of the SW Mediterranean.

For Guerrera *et al.* (2012), the Numidian turbidites were fed by a variety of fans that were small compared with the size of the basin (Fig. 2b). For Critelli *et al.* (2017) and Fornelli *et al.* (2019), the Numidian sandstones were deposited in elongate strips (fairways) fed from a narrow entry point (broadly along what is now northern Tunisia; Fig. 2c). In both scenarios illustrated in Figure 2b and c, the ocean basin also received sediment from the fledgling orogen to the north. Neither provides explanations for how deposits from these systems remain distinct from each other, an issue we address below.

The Numidian deposits have been swept up within tectonic units of the Maghrebian chain and southern Apennines and carried onto the orogenic forelands of Apulia and the Hyblean plateau of SE mainland Italy and Sicily respectively (Fig. 3a). These translations involved substantial tectonic rotations, of up to *c.* 100° (e.g. Speranza *et al.* 2003; Monaco and De Guidi 2006; Barreca and Monaco 2013). The Sicilian outcrops experienced clockwise rotations whereas those in the southern Apennines have experienced an anti-clockwise rotation (Fig. 3b), essentially corresponding to 'double saloon doors' (in the sense of Speranza *et al.* 2003; Martin 2006). Restoring the Numidian outcrops by applying counter-rotations reveals that they define a broad SSW–NNE-trending tract (Fig. 3c), similar to part of that proposed by Critelli *et al.* (2017; Fig. 2c).

In the eastern Maghrebian and southern Apennine orogens described here, the Numidian system was deposited upon Mesozoic and early Cenozoic substrata exclusively comprising carbonates, marls and mud-rocks. These attributes, as introduced above, make the Numidian sandstones ideally suited for use as tectonic tracers: we can deduce that all quartz clasts must have transited the basin

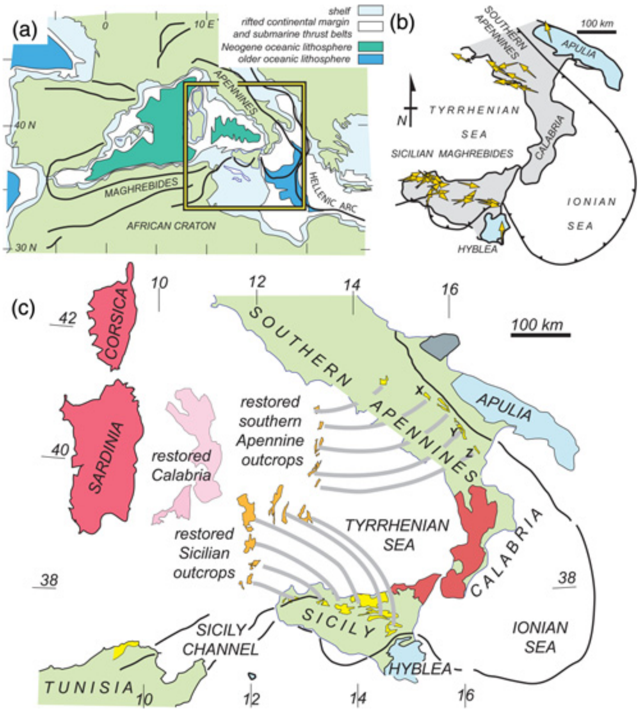

Fig. 3. Simplified location map for sedimentary basins in the western–central Mediterranean. The boxed area shows the more detailed map of (**c**). (**b**) Palaeomagnetically determined tectonic rotations for Mesozoic–Paleogene strata in Sicily and the southern Apennines (after Critelli *et al* 2017). Palaeo-north indicated by yellow arrows. (**c**) Location of the main outcrops of Numidian sandstones in Sicily and the southern Apennines, modified after Pinter *et al.* (2018). The restoration uses the tectonic rotations in (**b**).

system between their source area and their ultimate site of deposition without contamination from other clastic sources. Therefore, we can use the deposits to infer flow processes and the nature of the pathways down which the causative flows were routed.

The Numidian system in Sicily

The most widely studied parts of Numidian system in the Central Mediterranean are those in Sicily where they are incorporated into the thrust belt of the eastern Maghrebian chain (Fig. 4). The thrust belt is largely composed of Mesozoic and Paleogene carbonates, mudstones and marls generally inferred to have formed parts of the rifted continental margin of Africa into the Tethyan ocean. These pre-orogenic strata, apparently from distinct palaeogeographical domains from the margin, are now stacked in a series of thrust sheets that juxtapose Mesozoic platform and basin systems (Butler *et al.* 2019, and references therein). In most reconstructions these juxtapositions are assumed to reflect displacements during thrust sheet emplacement (e.g. Guerrera *et al.* 2012). However, deep-water Paleogene strata (the Argille Varicolori Formation; e.g. Ogniben 1960) locally overlie all the various Mesozoic palaeogeographical domains, indicating a period of restructuring before the Maghrebian thrust systems developed (Butler *et al.* 2019). The Numidian successions were deposited upon these complex substrates and represent the first influx of quartz sand into this part of the Mediterranean basin for over 200 myr. Regional palaeoflow was from west to east, in the modern reference frame (Pinter *et al.* 2016, 2018).

Stratigraphic context

The lower to middle Miocene strata show significant variations across Sicily, illustrated in a series of schematic composite stratigraphic columns (Fig. 5a) and tied in a chronostratigraphic chart (Fig. 5b). Until recently, the age of the Numidian succession has been significantly misinterpreted, largely because of the inclusion in published fossil assemblages of microfauna reworked from older strata (a common source of contamination in turbidites) and the lack of relative stratigraphic control of sample sites. To correct this, in our precursor studies we collected microfossil assemblages from logged sections where simple stratigraphic superimposition provided tests of relative age. Microfossil assemblages were screened for reworked material. The resultant age patterns (Fig. 5b) are reproducible and resolve the Numidian of the Nebrodi basin of northern Sicily (Fig. 4) to be Aquitanian to late Burdigalian in age (Pinter *et al.* 2016). In central–east Sicily, the Numidian is slightly younger with ages of up to late Langhian (Pinter *et al.* 2018).

In the Nebrodi Mountains, northern Sicily (Fig. 4), the Numidian successions (Pinter *et al.* 2016) chiefly lie unconformably upon Cretaceous platform carbonates of the Panormide palaeo-tectonic domain (e.g. Dewewer *et al.* 2010; Fig. 5a, column A). The Numidian is capped by a distinctive series of turbidites, termed the Reitano Flysch (Grasso *et al.* 1999). Outliers of Reitano Flysch unconformably overlie Numidian turbidites that are folded into their substrate of Argille Varicolori Formation (Fig. 5a, column B). These Numidian rocks include Langhian fauna (Pinter *et al.* 2018), as does the Reitano Flysch above, indicating that significant deformation and erosion happened during this short stage.

In central Sicily (column B in Fig. 5b), many parts of the Numidian succession build up from brown claystones, which we infer to represent deposition from turbidity currents that carried their coarser grain-size fractions elsewhere (Pinter *et al.* 2018). The first influx of medium to coarse sand (Burdigalian) represents switching of the main pathways of turbidity currents into these parts of the basin. In central Sicily, higher in parts of the Numidian successions

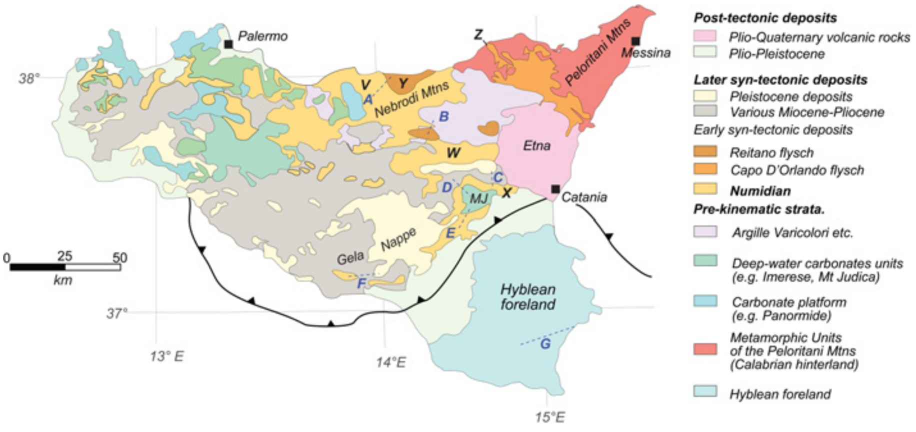

Fig. 4. Simplified geological map of Sicily showing location of schematic stratigraphic sections (A–G; Fig. 5) and simplified logged sections (V–Z; Fig. 6). MJ, Monte Judica. Modified after Lentini and Carbone (2014).

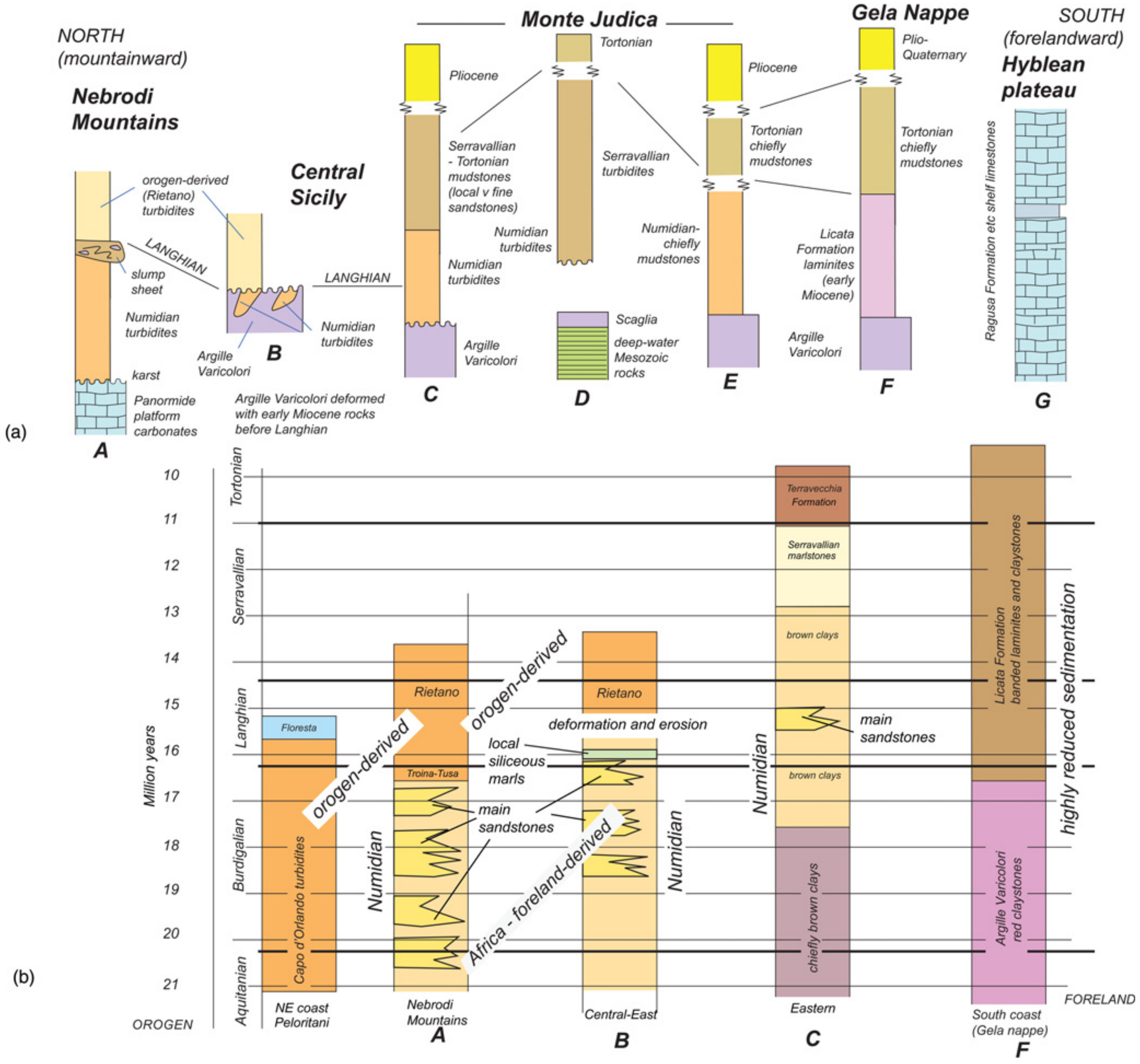

Fig. 5. (**a**) Schematic stratigraphic columns across Sicily showing the relationships between the Numidian system and encasing strata (modified after Butler *et al.* 2019). The locations of these sections are shown (A–G) in Figure 4. (**b**) Chronostratigraphic diagram for Sicily (using information given by Butler *et al.* 2019, and references therein).

the units are capped by siliceous marlstones, dated as Langhian (Pinter *et al.* 2018). These deposits we interpret as recording the deviation of the main turbidity currents to other parts of the basin, leaving the marlstone areas relatively sediment-starved.

In eastern Sicily, around the thrust culmination of Monte Judica (MJ in Fig. 4), Burdigalian strata are characterized by thick series of brown claystones, inferred to be part of the Numidian succession (Fig. 5a, columns C, D and E; e.g. Lentini & Carbone 2012), presumably deposited off the main conduits for sand flux. Here, significant sand bodies are restricted to Langhian-aged parts of the series (Pinter *et al.* 2018). They pass up into further mudstone and thin-bedded fine sandstones of Serravallian to Tortonian age.

The frontal (currently southern) parts of the thrust belt, represented by the so-called Gela Nappe (location shown in Fig. 4), contain a rhythmically banded marl with hard-grounds, the Licata Formation (Fig. 5, column F; Grasso *et al.* 1997). This deep-water unit essentially charts very limited deposition and is interpreted to have lain laterally far from and above the routes followed by the Numidian turbidity currents. It lies on multi-coloured mud-rocks (the Argille Varicolori Formation) of Oligocene and older age. Any lateral transition between the Licata Formation and the brown clays is unrecognized, potentially hidden by subsequent thrusting. The foreland area of the Hyblean Plateau saw shallow-water carbonate deposition (Fig. 5a, column G).

Northern Sicily contains a variety of Miocene turbidites, including the Capo d'Orlando 'flysch' (Bonardi *et al.* 1980). These lie unconformably upon Variscan metamorphic basement and metamorphosed Mesozoic cover, generally inferred to represent part of the Calabrian orogenic belt (e.g. Lentini 1982), preserved within the Peloritani Mountains of Sicily (Fig. 4). The Capo d'Orlando turbidite succession includes pebbles of crystalline basement but is generally characterized by thick beds of medium-grained immature sandstone with lithic fragments and detrital mica derived from the Calabrian basement rocks. The Capo d'Orlando turbidites are locally unconformably overlain by late Burdigalian to early Langhian 'Calcareniti di Floresta' (Aldega *et al.* 2011). These carbonate sandstones are reworked from earlier carbonate formations preserved within the Peloritani Mountains. Collectively the Floresta and Capo d'Orlando units are broadly the syntectonic cover to the Calabrian thrust sheets, deposited in thrust-top basins.

Calabria-derived turbidites that overlie the Numidian system or its immediate substrate are termed 'Reitano flysch'; Fig. 5a, A and B; Grasso *et al.* 1999). These unconformable units include thin medium- to fine-grained volcaniclastic sandstones generally referred to as the 'Troina–Tusa flysch' ('Tufiti di Tusa' of Q7 Ogniben 1960). De Capoa *et al.* (2012) showed that at least some material was derived from Miocene volcanic rocks in Sardinia (essentially part of the Calabrian orogen).

The Calabrian-derived flows (feeding the Troina–Tusa, Reitano and Capo d'Orlando turbidites) and those from north Africa (feeding the Numidian turbidites) remained distinct. That these systems do not mix indicates that the broad basin area between the fledgling Calabrian orogen and the foreland was structured. At least some of this structuring must have happened during the Langhian (Fig. 5b) so that Numidian sand deposition could continue in the Mont Judica area (Fig. 5a, column C) whereas Reitano turbidites were restricted to the north (Fig. 5a, columns A and B). Coeval strata now preserved in thrust sheets to the south in Sicily are dominated by mudrocks and marlstones (and carbonates on the foreland) indicating that the sandy turbidity currents did not transit these areas of the basin. There are no purely African-derived sandstones younger than Langhian that have been identified in Sicily. Where preserved, the Numidian successions pass up into mudstones. Younger sandstones in Sicily (Serravallian and younger) exclusively rework previous deposits from the thrust wedge or are derived from the Calabrian orogen.

Several existing facies models have been erected for the Numidian that use variations in the proportion of sand to silt/mud, thicknesses and stacking pattern of beds, and these schemes have in turn been tied to models of unconfined turbidite fans (e.g. Guerrera *et al.* 2012). This approach has assumed that different facies were deposited in distinctly separated parts of submarine fans and their current proximity has resulted from tectonic juxtaposition of later, Q8 far-travelled thrust sheets (e.g. Bianchi *et al.* 1987). Thus, Numidian stratigraphy has directly influenced cross-section-scale interpretations of structural geometry (Butler *et al.* 2019). However, recent stratigraphic and sedimentological field research on the Numidian of Sicily, allied to geological mapping (Pinter *et al.* 2016, 2018), has revealed continuous, transitional stratigraphic sections and lateral connectivity between different facies previously interpreted as having been far removed. There are mappable lateral pinch-outs of sandstone bed-sets and onlap onto substrate. These short-range (3–5 km) facies changes and substrate relationships are not consistent with unconfined submarine fan models.

Sedimentology

Full detailed descriptions and interpretations have been provided by Pinter *et al.* (2016, 2018) and only a brief summary is provided here. As noted above, the Numidian turbidites in Sicily are characterized by exceptionally mature quartz sandstone (Fig. 6a). There are significant thicknesses of coarser material with quartz granules and pebbles up to 5 cm in diameter (e.g. Thomas and Bodin 2013; Fig. 6b). Classically described as structureless or massive (e.g. Johansson *et al.* 1998, and references therein), this outcrop character reflects the exceptional sorting and locally extensive dewatering and local liquification of the deposits (Fig. 6c). When not dewatered, the majority of the sandstones contain parallel lamination (e.g. Fig. 6d). In some locations, the coarse facies contain clasts of fine-grained carbonates and mudstones (Fig. 6e) that can be readily correlated with substrate lithologies from the basin floor (Pinter *et al.* 2018). There are also rare, well-rounded clasts of Numidian sandstone. We interpret these clasts as recording erosion by the causative turbidity currents both of basin-floor substrate and of slightly older Numidian sediment.

The Numidian facies contrast markedly with the Capo d'Orlando (Fig. 6f) and Reitano turbidites (Fig. 6g), which are characterized by diverse sand compositions with lithic fragments that include metamorphic and granitic material indicative of a source from the fledgling Calabrian orogen. These too have coarser-grained components including thick conglomerates. As with the background sandstone, conglomerate clast types are highly variable (Fig. 6h).

Typically, sandstones of the Numidian system form units several tens of metres thick that can commonly be shown to be amalgamated (Fig. 7a), with individual depositional units generally between 50 and 200 cm thick. The amalgamated bed-sets show various stacking patterns. In places, especially within northern Sicily, the bed-sets combine to create units several hundred metres thick (e.g. Fig. 7b). More commonly, the sandstone bed-sets are separated by finer-grained, thinner-bedded units (Fig. 7c). Individual bed-sets can be traced for several kilometres, through continuous Numidian outcrop. The outcrop of Numidian strata includes finer-grained, more thinly bedded sandstones (Fig. 7d), siltstones and mudstones (e.g. Fig. 7e). Early studies (referenced by Guerrera *et al.* 2012) interpreted the various facies of the Numidian to originate from widely separated parts of unconfined submarine fans and they have been assigned to distinct stratigraphic formations and interpreted to lie in different thrust sheets. Our mapping in northern Sicily (Pinter *et al.* 2016) demonstrates that the amalgamated sandstones (specifically the outcrops in Fig. 7b) pass laterally into the thin-bedded facies over 3–5 km, approaching an unconformity with Mesozoic substrate. We therefore conclude that the various facies represent lateral changes in the behaviour of causative flows, with the amalgamated sandstones lying in the main flow path and the thin beds being marginal to the flow pathway.

Stratigraphic sections of Numidian sandstone vary in thickness from up to 1500 m to less than 200 m (Fig. 8). Full detailed logs have been provided by Pinter *et al.* (2016, 2018). Beds invariably show abrupt grain-size breaks with coarse sand grade material passing directly into very fine sand and silt. Even in thin sandstone facies (e.g. Fig. 7d), medium to fine sand grade passes abruptly up into silt. Collectively these relationships, as laid out by Stevenson *et al.* (2015), imply substantial sediment bypass. The main amalgamated sandstone bed-sets (e.g. Fig. 7a–c), especially where they contain granule- to cobble-sized grain suites, represent the main conduits for the causative turbidity currents. They represent parts of sand fairways that, prior to later tectonic disruption, would have formed continuous ribbons across the basin. Several locations contain thick, marly intervals that imply transient shut-downs in sand supply. This is interpreted as reflecting temporary re-routing of causative turbidity currents and clastic starvation in parts of the basin. A general migration of sand fairways from, in current orientation, north to SE across eastern Sicily is inferred from the diachroneity of thick sandstones established from the biostratigraphy of the associated mudstones (Pinter *et al.* 2018). Collectively, we deduce that the Numidian system in Sicily was confined but uncontained, with the causative flows directed along sinuous corridors across the basin.

The sedimentology of the Reitano turbidites is significantly different from that of the Numidian (Fig. 9a). As noted above, the Reitano is preserved in distinct stratigraphic outliers, in places unconformably overlying a deformed substrate of Numidian turbidites and its own substrate of Argille Varicolori Formation (e.g. Fig. 9b). As a system, it too shows significant variations in grain size, with coarse fractions up to cobbles (20–30 cm diameter clasts). Sandstone beds can be amalgamated into thick bed-sets (Fig. 9a). However, where bed tops are not eroded by younger units

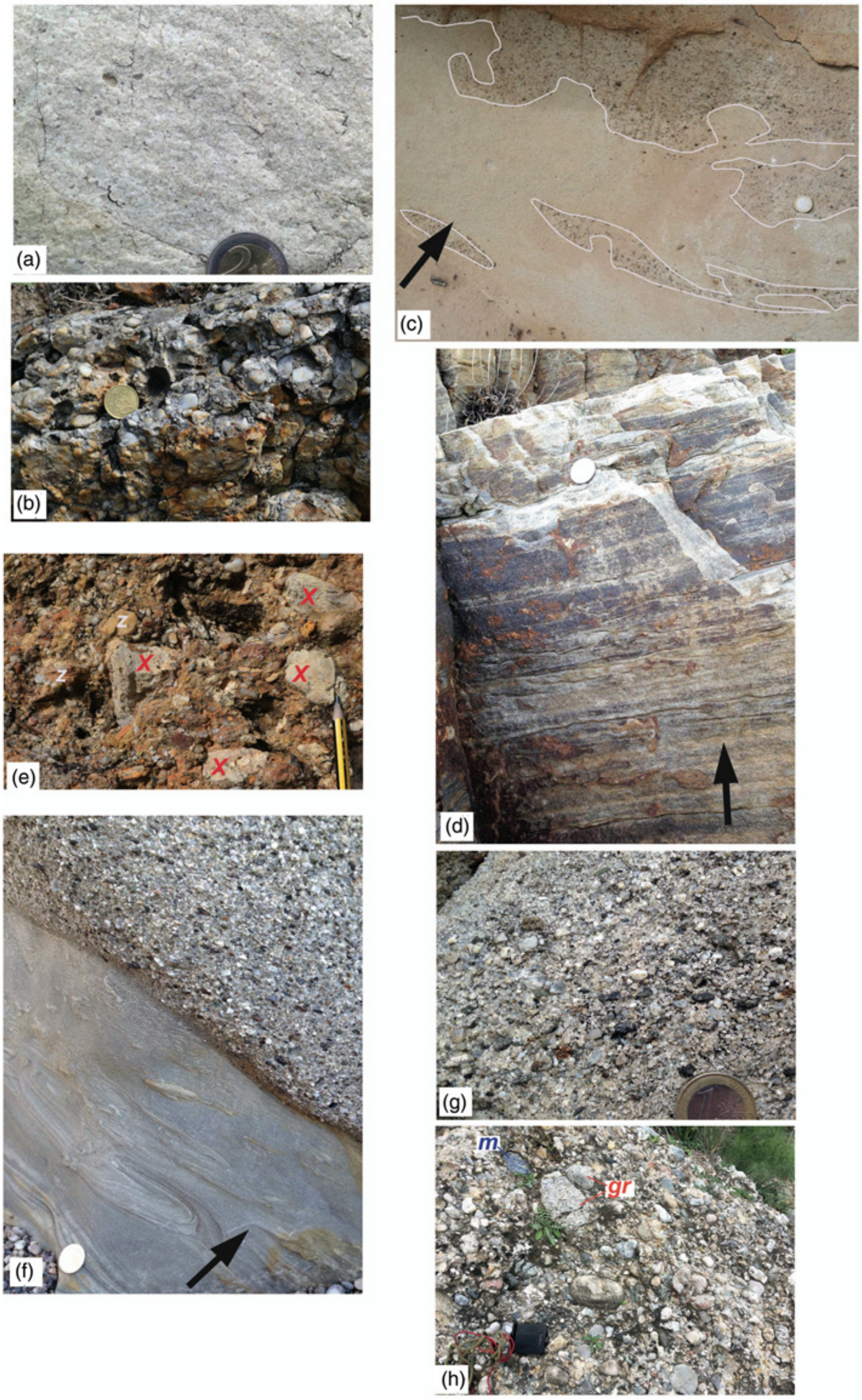

Fig. 6. The character of Numidian and time-equivalent units in Sicily. Where visible, the coins are all 2.5 cm in diameter. Younging directions shown by black arrows. (**a**) Coarse-grained, well-sorted quartz sandstone typical of the Numidian sandstone. (**b**) Pebbly facies in the Numidian comprising granules to large pebble-grade quartz clasts, Finale, northern Sicily. (**c**) Liquified medium to coarse Numidian sandstone with foundered bodies of small to medium pebbles. Remobilization and associated dewatering are common in much of the Numidian Sandstone, obscuring primary depositional fabrics; lower Troina valley, eastern Sicily. (**d**) Primary depositional lamination in Numidian sandstone, Finale, northern Sicily. (**e**) Detail of a coarse bed base with outsized clasts of micritic limestone (x, interpreted to be ripped-up, poorly lithified fragments of the Eocene Polizzi Formation; micritic limestones, part of the basin floor; see Pinter *et al.* 2018), together with rip-up clasts of earlier parts of the Numidian sandstone (labelled Z), Pietra Pirciata, eastern Sicily. (**f**) Coarse facies of Capo d'Orlando turbidites in their type area on the north coast of Sicily. Both the medium sandstone (below) and granule–small-pebble unit above contain diverse clast compositions. (**g**) Typical coarse facies from the Reitano turbidites with diverse clast compositions. (**h**) Conglomeratic facies within the Capo d'Orlando units in the southern Peloritani Mountains (Malvagna area). gr, granite; m, metamorphic clasts. Otherwise the bulk lithic clast type here comprises limestones.

they commonly grade upwards from coarse sand through finer sand grades into silty bed caps. Generally, the sandstones are dewatered but primary parallel lamination is common. Finer sand-fractions towards bed tops commonly show convolute lamination. Away from amalgamated bed-sets, individual sandstone beds commonly have with mud caps locally attaining thicknesses of several metres (Fig. 9c). 'Sandwich units', where individual beds have interiors of muddy debrites and remobilized laminated sands contained between bed tops and bases of well-sorted sandstone, are common (e.g. Fig. 9d). These hybrid beds (in the sense of Haughton *et al.* 2009) are common constituents of ponded turbidites, as might be expected in confined–contained systems (Southern *et al.* 2015). The presence of thick mud-caps and the associated propensity for hybrid beds is consistent with our deduction that the causative flows of the Reitano turbidites were ponded within mini-basins developed above a deforming thrust wedge that had incorporated earlier Numidian turbidites.

Summary

The sedimentology and map geometry of Numidian deposits in Sicily indicate that they are part of a confined but uncontained turbidite system. The present-day outcrop has been strongly modified by later thrusting but the overall disposition of units from north to south across the island has not been (Butler *et al.* 2019). Pinter *et al.* (2016) showed that the Numidian sand system in

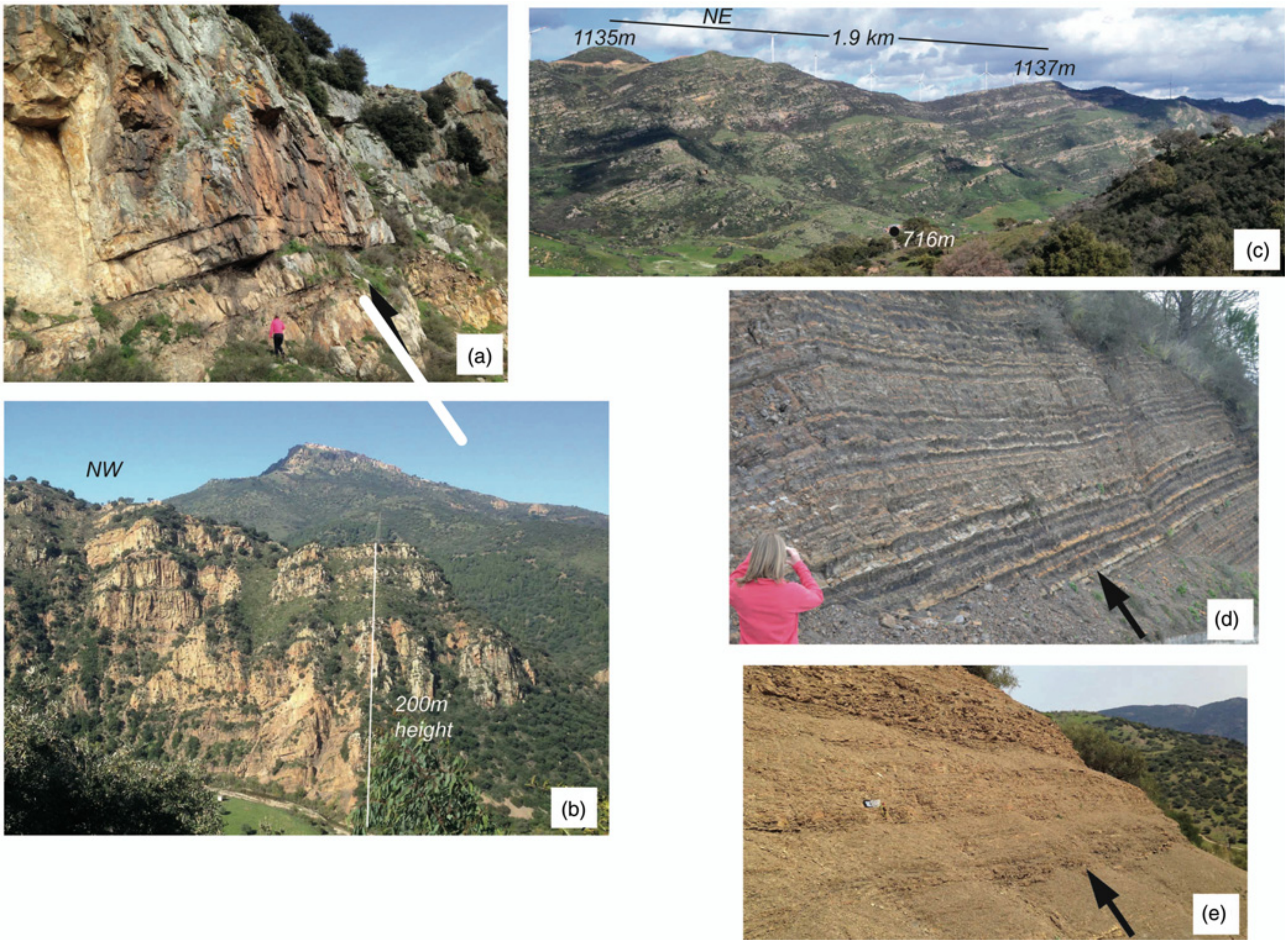

Fig. 7. Numidian outcrops in Sicily. (**a**) illustrates the amalgamated nature of the thicker sandstone units, near Mistretta, northern Sicily. (**b**) The Pollina section (see Pinter *et al.* 2016). (**c**) Monte Salici, central Sicily (see Pinter *et al.* 2018). (**a**–**c**) show strata interpreted to typify the main sand fairways for the Numidian turbidites. (**d**) Thin-bedded sandstones and siltstones, representative of off-fairway deposition, inferred to lie on the flanks of the main conduits for causative turbidity currents. These outcrops lie c 5 km lateral to (SSW of) the Pollina section (**b**). (**e**) Brown siltstones and fine sandstones, again lateral to (**b**) and (**d**). (See Pinter *et al.* (2016) for further details.)

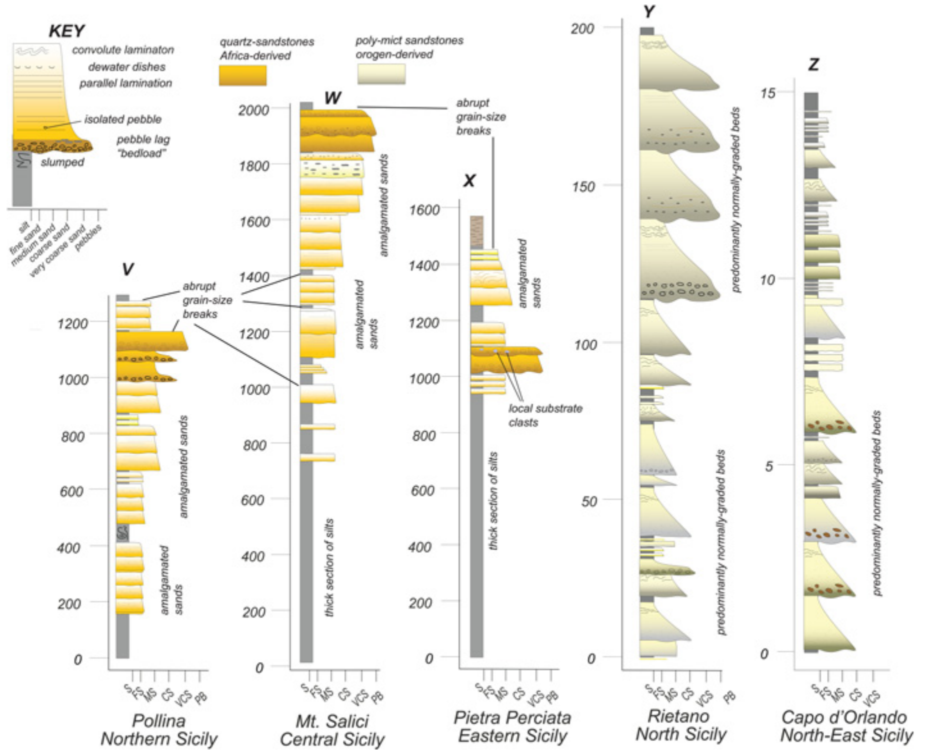

Fig. 8. Schematic logs contrasting various parts of the Numidian system in Sicily with the broadly time-equivalent turbidites of the Capo d'Orlando and Reitano systems. The detailed logs upon which these schematic versions are based were published and their locations given by Pinter *et al.* (2016, 2018). The locations are shown schematically in Figure 4 (V–Z).

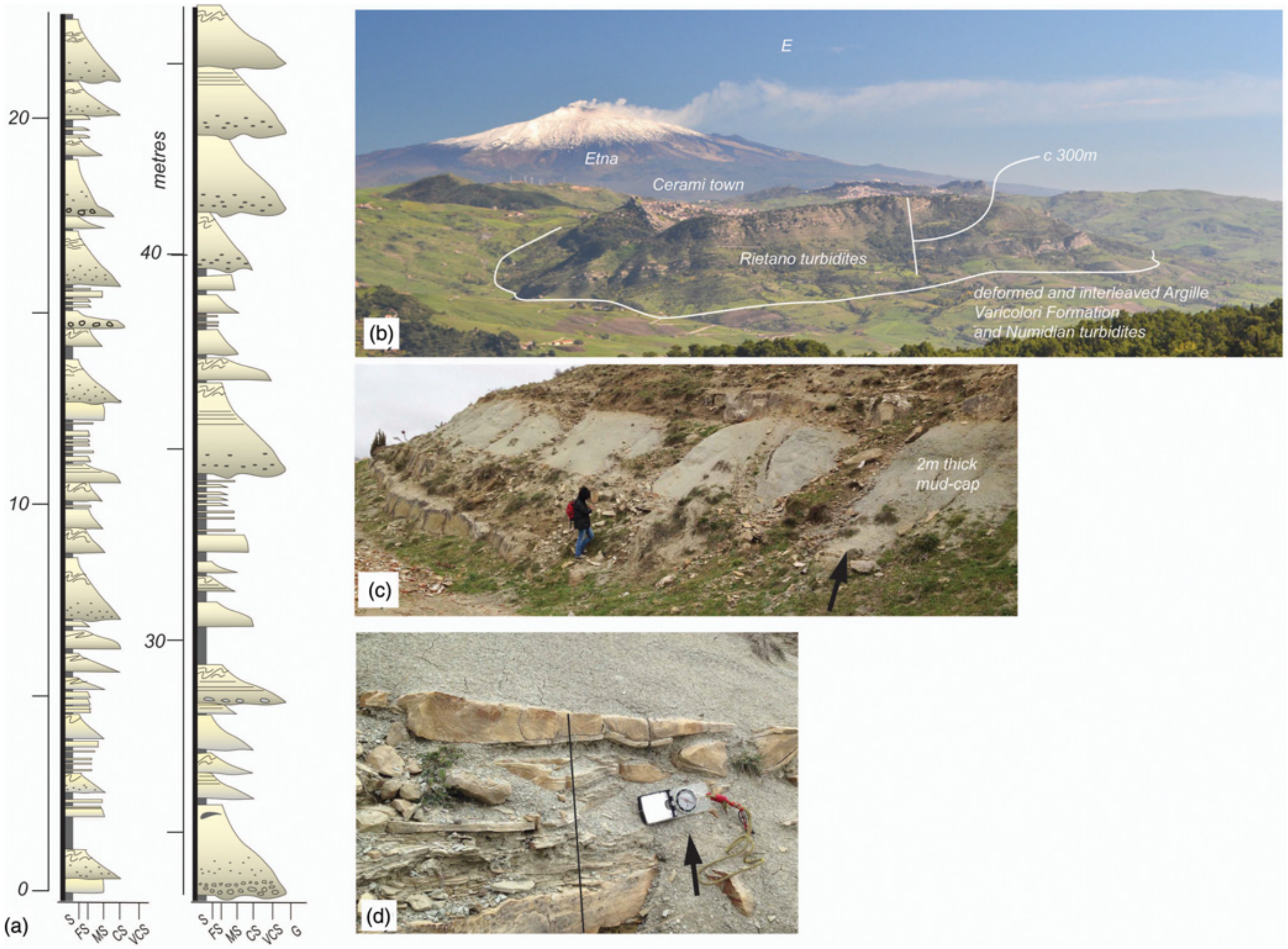

Fig. 9. Characteristics of the Reitano system. (**a**) A log from the Reitano outlier on the north coast of Sicily (UTM coordinates 436023.00 m E, 4207089.00 m N) showing the typical grading within sandstone beds (key as in Fig. 8). (**b**) One of the stratigraphic outliers, cropping out around the town of Cerami, eastern Sicily. The Reitano turbidites (Langhian) lie in an open syncline and unconformably overlie deformed Argille Varicolori Formation together with tightly infolded Numidian sandstone (as represented in column B in Fig. 5a). (**c**) The preservation of thick mud caps interbedded with fine to medium sandstones, Cerami town. Younging direction indicated by black arrow. (**d**) A typical sandwich hybrid bed (extent of single bed shown by bar), Cerami town.

Sicily was deposited in structurally confined conduits, apparently controlled by embryonic thrust structures that deformed the basin floor. The development of thick sandy bed-sets without significant incision is consistent with these being deposited from confined–uncontained turbidity currents (e.g. Liu *et al.* 2018). These sand fairways are locally controlled by active thrusting. The chronostratigraphy of the Numidian system (Fig. 5b) shows a southward migration of the principal sand fairways through time (from Burdigalian to Langhian) and the northern parts of the system are overlain by the orogen-derived Reitano turbidites. That the sedimentology of the Reitano is consistent with deposition by confined–contained flows indicates that thrust-top basin morphology remained during subsequent deformation. Active thrusting therefore served to keep the orogen-derived (Reitano) and African-derived (Numidian) sand systems distinct at least within the preserved outcrops of Sicily. The effect of active thrusting was to confine the causative turbidity currents of the Numidian so that suspension clouds could carry medium to lower coarse sand grains through the conduits and, by entraining bed-load, deliver pebbles and granules to the furthest parts of the system exposed in eastern Sicily. The Numidian of western Sicily (back upstream) remained a deep-water deposit. Any coastline in the early Miocene must have lain yet further upstream. The present minimum separation between the downstream Numidian outcrops of eastern Sicily and the closest possible coastline exceeds 200 km. Therefore, we deduce that the causative turbidity currents flowed at least this far into the ancestral Mediterranean. However, more outcrops of Numidian strata lie in the southern Apennines (Fig. 3c) and these provide further insights on the extent of the system and the efficiency of its causative flows.

The Numidian system of the southern Apennines

The outcrops of Numidian in the southern Apennines are found in the eastern part of the Campania–Basilicata region, where they occur as a series of ridges from Monteverde to Valsinni (Fig. 3c). That these sandstones form part of the same depositional system as found in Sicily is confirmed by the African sand provenance (e.g. Fornelli *et al.* 2015, 2019; Critelli *et al.* 2018). The Numidian in the southern Apennines lies upon a Cretaceous–Oligocene succession of mudstones and marlstones with thin interbedded carbonates, the so-called Flysch Rosso (e.g. Zuppetta *et al.* 2004). Clay chemistry indicates a weathered Archean basement source, presumably the African craton (Mongelli 2004). This succession is part of the Lagonegro–Molise basin and it is time- and facies-equivalent to the basinal mudstones of the Argille Varicolori Formation described for the central–east Sicilian Numidian basin. Collectively the Numidian and its Mesozoic substrate evolved into a major thrust sheet, the Lagonegro allochthon, that was emplaced onto the

Apulian foreland by counter-clockwise rotational overthrusting, chiefly in the late Miocene and Plio-Quaternary (e.g. Mazzoli *et al.* 2006). These results concord with the Numidian sandstones of the southern Apennines having been deposited during the Langhian (Patacca *et al.* 1992; D'Errico *et al.* 2014; Critelli *et al.* 2017). These age constraints are supported by the age of successor deposits in southern Italy (e.g. Zuppetta *et al.* 2004; Critelli *et al.* 2018).

The data collected from the Numidian sections of the southern Apennines comprise three sedimentary logs, which represent key parts of the system. We use these data together with sedimentary observations to evaluate facies and then depositional processes. The selected sections are described from the northernmost part of outcropping succession (Monteverde) to the southernmost part (Valsinni section).

Monteverde (Elephant House section)

The Numidian succession in Monteverde (location X in Fig. 3c) chiefly comprises a thick interval of fine-grained sandstones and siltstones at the base that coarsens upwards. This locality has proven important for establishing a north African provenance for the Numidian of the southern Apennines (Fornelli *et al.* 2015). Notwithstanding rather sparse outcrop, a stratigraphic thickness is estimated to exceed 100 m.

The lower parts of the Monteverde section are characterized by medium- to thick-bedded sandstones of 0.1–1 m thick, composed by clean quartz grains of medium to fine grain sizes (Fornelli *et al.* 2015). The sandstones are generally ungraded or weakly graded and present a typical grain-size break in the top contact (in general, from medium sands to silts). The basal contact is generally concordant or slightly erosive (*c.* 1 cm). The sandstones are interbedded with finer-grained intervals of siltstones, with rare thin-bedded sandstones of maximum 2 cm thickness. The siltstone intervals are laminated or massive, with common debritic aspect. Rare quartz granules are found encased in the debritic intervals. These interbedded fine-grained intervals are concordant with the sandstone bedding, which overall forms a tabular geometry for the deposits.

The stratigraphic top of the Monteverde section and passage to younger formations is unknown. The upper part of the preserved section is characterized by more amalgamated coarse sandstones with pebbly intervals. The short section, at the Elephant House in Monteverde town (Fig. 10a), is representative of this facies. Amalgamated bed-sets form a 7 m thick package of sandstone. Depositional banding defined by grain-size variations occurs in this amalgamated package and individual sandstone beds are a maximum of 1 m thick. The sandstones are poorly graded to ungraded, composed of well-sorted, very coarse to granular sands. Although beds appear to be massive and unstructured, careful observation reveals weak parallel lamination and banding (Fig. 10b), which is otherwise obscured by diffuse pipes, dish and disaggregation textures indicative of dewatering processes. Although the sands are otherwise well sorted, there are many outsized granules and isolated pebbles (up to 2 cm in diameter) dispersed through the sandstone (e.g. Fig. 10c). These coarse fractions are also present as lags at the base of the sandstone beds, with shallow erosional relief of a maximum of 5 cm. Otherwise, bed bases are flat.

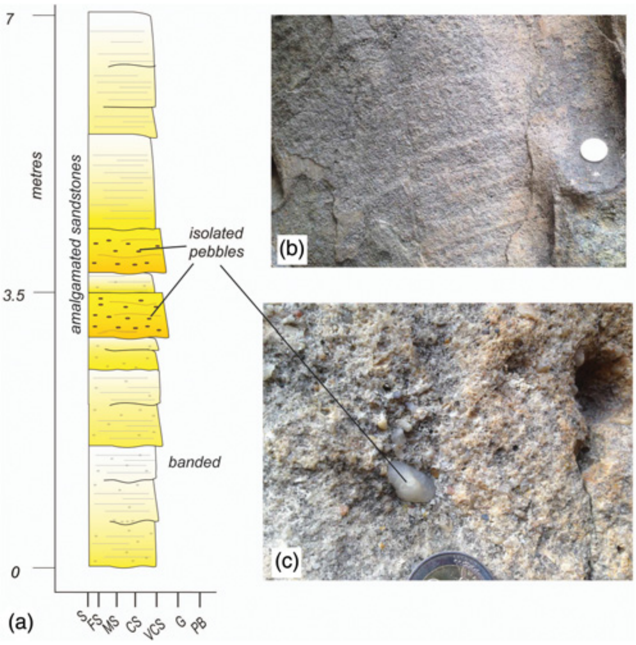

Fig. 10. Sedimentology of amalgamated Numidian sandstone bed-sets at the 'Elephant House' outcrop, Monteverde (UTM coordinates 544902.00 m E, 4539451.00 m N). (**a**) Sedimentary log (key as in Fig. 8). (**b**) Diffuse depositional banding (at *c.* 4 m on log). (**c**) Example of granules and dispersed pebble (at *c.* 3.2 m on log). Coin in both photographs is 2.5 cm in diameter.

Salandrella section, Accettura

The Numidian succession in the Accettura area (location Y in Fig. 3c; Selli 1962; Boenzi *et al.* 1968) is steeply dipping, with a stratigraphic thickness exceeding 450 m (D'Errico *et al.* 2014), and generally coarsens upwards. A representative log for the upper part of the section is provided here (Fig. 11a). It is characterized by alternations of thick-bedded sandstones and thin-bedded fine-grained sandstones and siltstones. The lower part of the section is characterized by amalgamated bed-sets of sandstones up to 10 m thick, with individual sandstone beds of at most 2 m thickness. Further amalgamation of stacked sandstone beds characterizes the preserved top of the section (e.g. Fig. 11b). The sandstones are ungraded or slightly graded, well sorted and medium grained, with parallel lamination and rare convolute lamination towards bed tops. However, most bed tops are sharp, with distinct grain-size breaks from medium sand passing abruptly into siltstones (e.g. Fig. 11c). These sandstones are characterized by weakly normally graded coarse sands with granules and small pebbles on bed bases. Outsized quartz granules are distributed through beds that otherwise show parallel lamination defined by weak alignment of coarser grains. Bed bases are slightly erosive (*c.* 5 cm). The thick sandstone beds are interbedded with thin-bedded fine to medium sandstones with siltstones up to 1 m thick. The thin-bedded sandstones are ungraded or slightly graded medium to fine grained with tabular, flat bed bases and tops. Where exposed, the siltstones are grey, laminated or massive.

The Numidian of the Salandrella section passes upwards into the arenaceous–calcareous deposits of the Serra Palazzo Formation. The Serra Palazzo sandstones comprise texturally and compositional diverse clasts (metamorphic, granite together with quartz, including angular pebble-grade material). They are interpreted to represent the first significant input of coarse clastic material into this part of the basin from the developing orogen.

Colobraro–Valsinni

The Numidian succession at Colobraro in Valsinni (location Z in Fig. 3c; Lentini *et al.* 2002; Zuppetta *et al.* 2004) crops out in a ridge that forms a NNW–SSE monocline structure and the section reaches 800 m in thickness (Carbone *et al.* 1987). The site was important for establishing a mid- to late Langhian age of Numidian sand deposition in the southern Apennines (D'Errico *et al.* 2014). A representative part of this succession is shown in Figure 12. It is characterized by amalgamated bed-sets of sandstones of up to 15 m

Q9

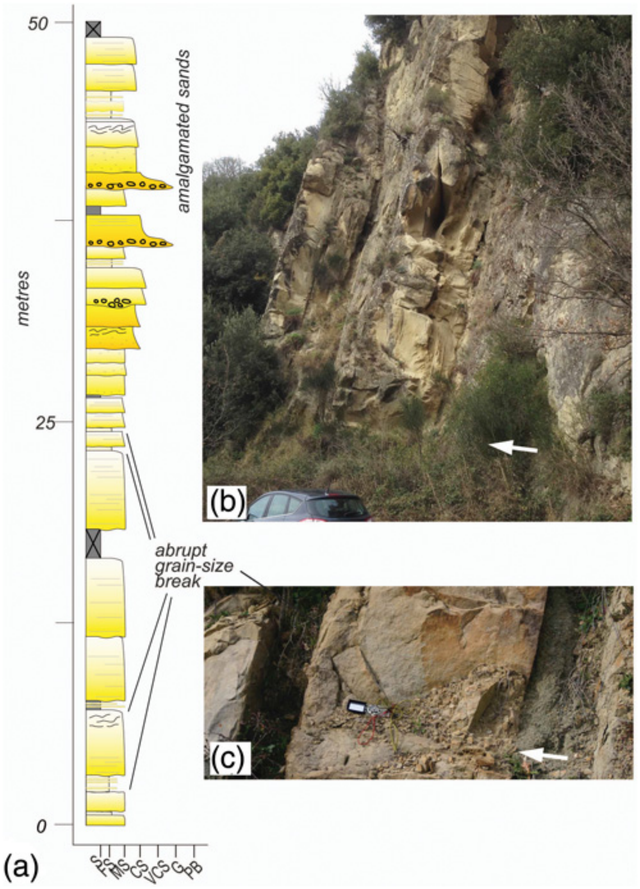

Fig. 11. Sedimentology of the Numidian succession in the Salandrella valley, north of Accettura town (UTM coordinates 598039.00 m E, 4483247.00 m N). It should be noted that the section is subvertical owing to later tectonic deformation, and youngs to the SW (left in photographs, as arrowed). (**a**) Sedimentary log (key as in Fig. 8). (**b**) Oblique view onto amalgamated sandstone beds (top part of section). (**c**) Typical sandstone bed (mid-section in (**a**)) showing planar base and top, with abrupt transition at top into silt to very fine sand cap (compass for scale).

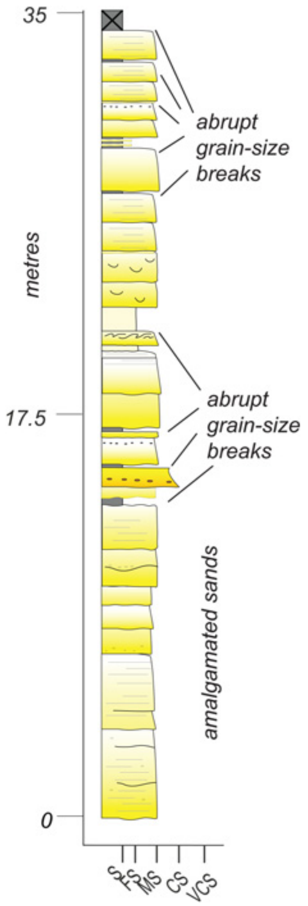

Fig. 12. Representative log of stacked bed-set in the Numidian at east of Colobraro village, Valsinni (UTM coordinates 621273.00 m E, 4449771.00 m N). Key as in Figure 8.

thick, with individual sandstone beds of a maximum of 1 m thick separated by thin intervals of fine-grained facies (a few centimetres thick). The sandstones are generally composed of ungraded well-sorted medium sand, with coarse sand intervals restricted to bed bases and lags. Crude parallel lamination is observable in most beds, but is otherwise obscured by dewatering pipes. The fine-grained facies are characterized by thin-bedded sandstones of a maximum of 3–4 cm thick, interbedded with laminated siltstones. The thin beds are ungraded medium-grained sandstones with rare convolute lamination.

The Numidian of the Colobraro–Valsinni section passes upwards into a thick sequence composed of marlstones and arkosic sandstones called the Serra Cortina Formation (Lentini *et al.* 2002). We interpret these strata as being derived from the fledging Calabrian–Apennine orogen, essentially equivalent to the Serra Palazzo Formation in the Salandrella section. However, these orogen-derived successions need not be fed from the same submarine fan system. Understanding their depositional systems alongside the tectonic controls would be an interesting study but is one that lies beyond the scope of our paper.

Other Miocene deep-water successions in the southern Apennines

The Albidona flysch includes upper Burdigalian to Langhian turbidites (Selli 1962; Cesarano *et al.* 2002) and so is broadly time-equivalent to the Numidian. It was sourced principally from the Calabrian arc (Cavuoto *et al.* 2004, 2007) and lies unconformably on the obducted Ligurian subduction–accretion complex preserved along the Tyrrhenian coast of the southern Italian mainland. The Albidona flysch changes in character up-section, from chaotic immature siliciclastic deposits at the base to turbiditic arenaceous–clayey material with thick intervals of marlstones towards the top (Finetti *et al.* 2005).

Further west in the orogen, the Burdigalian–Langhian turbidites of the Cilento group unconformably overlie strongly deformed and weakly metamorphosed deep-water successions ascribed to the Ligurian accretionary prism (Cammarosano *et al.* 2004). Cavuoto *et al.* (2007) described the Cilento Group as being orogen-derived. The system contains thick sandstones that are locally amalgamated. Strikingly, the Cilento system also contains rare calciturbidites with primary algal clasts and exceptionally thick (tens of metres) mud-caps. These megabeds are analogous to similar deposits in the Marnoso–Arenacea basin of the northern Apennines (e.g. the Contessa megabed; Gandolfi *et al.* 1983) and may have a similar provenance (a proto-Abruzzo carbonate platform in what is now the central Apennines). Their thick mud-caps indicate that these carbonate-rich flows were entirely contained (Fig. 1b), and therefore that the Cilento basin was isolated from the basin system that hosted the Numidian system.

Both the Albidona and the Cilento turbidites may represent a structurally equivalent unit to the Reitano and Capo d'Orlando turbidites of Sicily. As with the Sicilian examples, the Albidona–Cilento and Numidian systems do not appear to have mixed. Therefore, a similar explanation is proposed. The orogen-derived turbidites of the southern Apennines formed systems ponded in thrust-top basins. Their causative turbidity currents were contained by these basins and did not contaminate the Numidian sand fairway.

As noted above, in the southern Apennines, the Numidian is overlain by the Serra Cortina and Serra Palazzo formations, together with further orogen-derived sandstones of the Gorgoglione Formation (Critelli *et al.* 2017; and references therein). This indicates that by the Serravallian the Numidian sand system was not able to reach the southern Apennines.

Finally, mature quartz sandstones forming the Bifurto Formation unconformably overlie parts of the shallow-water limestones of the 'Apennine platform' (Selli 1957). Traditionally these sandstones are considered to be a distinct unit. However, zircon compositions reported by Fornelli *et al.* (2019) show the Bifurto and Numidian sandstones to have the same, African provenance, uncontaminated by clasts from the fledgling Calabrian orogen. For our purposes, the Bifurto can be considered to simply be part of the Numidian sand fairway. The variations in the Mesozoic geology of its substrate are similar to those discussed above for Sicily and imply substantial restructuring of the platform and basin morphology that was initiated during the Mesozoic. Consequently, the distributions of these Mesozoic rocks are unreliable guides to Miocene palaeogeography (Butler *et al.* 2019).

General observations

The Numidian outcrops of the southern Apennines are characterized by thick, tabular bodies that can be traced laterally for at least several kilometres, this extent being limited by outcrop quality and later deformation. Erosional features are limited to a few centimetres at the base of individual beds; there are no major incisional features into the underlying deposits. The sandstone-rich intervals are characterized by intense amalgamation of typically ungraded coarse to medium sandstones (e.g. Fig. 11b). These intervals pass abruptly into cogenetic very fine sandstones and siltstones, without showing a transition through intermediate grain sizes (medium and fine sands). In many cases, internal structures such as primary banding and parallel lamination are evident, suggesting that the beds were formed by progressive aggradation. There are no obvious associations with stacked finer sands as associated constructional levees. D'Errico *et al.* (2014) reported a general grain-size decrease from south to north in the southern Apennines. However, the major sand bodies are remarkably homogeneous across the region. Indeed, medium to coarse sands still represent the predominant grain sizes even in relatively distal areas, which also include pebbles (e.g. Fig. 10c from the Monteverde section; X in Fig. 3c).

Collectively the sedimentology, as for the Numidian sandstones of Sicily, suggests that the turbidity currents continued to largely bypass the basin floor. We deduce that the causative turbidity currents were strongly confined so that they maintained their sediment-carrying capacity. Although outcrop in the southern Apennines is not sufficient to demonstrate the lateral facies changes and relationships with substrate that we have been able to show in Sicily (Pinter *et al.* 2016, 2018), the apparent absence of significant incisional relationships or associated constructional levee facies suggests that confining bathymetry was provided by structures on the basin floor.

Through the Langhian, the Numidian sand fairway remained uncontaminated by orogen-derived sediments. Therefore, orogenic detritus (Albidona and Cilento turbidites) was ponded, presumably within enclosed thrust-top basins located higher on the westward slope of a seaway that lay east of the ancestral Calabrian mountain belt. The Numidian system lay towards the base of this seaway. However, this does not constitute a simple foredeep basin (see Guerrera *et al.* 2012). Rather, the basin floor was structured, presumably by fledgling thrust systems that went on to develop into the imbricate systems now found within the Lagonegro allochthon (e.g. Zuppetta *et al.* 2004).

The Numidian as a confined turbidite system across the central Mediterranean

The sedimentology of the Numidian sand system is not compatible with the depiction of Numidian fans as small and unconfined, with multiple input points both east and west of modern Sicily (Guerrera *et al.* 2012). Nor is it compatible with the single unconfined fan depiction of Thomas *et al.* (2010); Critelli *et al.* (2017; Fig. 2c) showed the Numidian system as forming elongate sand ribbons across a deep ocean basin then running up onto the Mesozoic Apulian platform (Fig. 2c). Fornelli *et al.* (2019) modified this model by showing the Numidian sandstone ribbons running across rift-related relict topography ahead of the Apennine–Maghrebian thrust front. We concur with Critelli *et al.* (2017) and Fornelli *et al.* (2019) that the Numidian system was fed axially, from the SW of the Sicilian thrust belt. As the foreland area, SE of modern Sicily, was essentially marine we deduce that there was no significant sediment influx from this direction. However, both of these other studies imply that turbidites lie in narrow pathways across an open marine basin (e.g. as illustrated in Fig. 2c) without discussing the basin structure necessary to generate these fairways. We now examine the relationship between the confined Numidian turbidites and the inferred basin structure.

The Numidian system conforms to models of confined turbidites, where causative turbidity currents are preferentially routed along elongate, structurally controlled conduits. This structural confinement of the causative turbidity currents was most plausibly provided by active thrust anticlines that developed within a deep-marine seaway. In our model (Fig. 13) the routing of turbidity currents effectively fractionates coarse sand and larger clasts from the finer-grained fractions. Sand was preferentially deposited along the main pathways taken by turbidity currents, forming fairways. Finer fractions, as well as being flushed through the system, accumulated on the flanks of the fairways and over-spilt into adjacent parts of the basin floor. Where fold amplification continues, sediment routing can evolve, delivering coarse sand to previously largely depleted or bypassed parts of the basin. Abandoned parts of previously active flow paths can become starved of significant detrital input. This evolution is broadly supported by the chronostratigraphy of the Numidian system in Sicily (Fig. 5b).

Not only do folds and the resultant seafloor relief control the behaviour and routing of the main Numidian turbidity currents, they can also serve to hold back detritus shed from the fledgling Calabrian orogen (Fig. 13). In the Sicilian part of our study, these orogen-derived materials include the Reitano turbidites. In the southern Apennines the Cilento turbidites, which also unconformably overlie deformation structures, represent a tectonostratigraphic unit equivalent to the Reitano of Sicily. Both systems are interpreted here to have been restricted to distinct thrust-top basins. There are no indications that significant sand components from these orogen-derived systems entered the flow pathways for the Numidian. Again, sediment type was fractionated by the structure of the basin.

As noted in our previous work in Sicily (Pinter *et al.* 2016, 2018), the Numidian sandstones overlie a variety of strata that originally were deposited under significantly different palaeobathymetries. Traditional accounts of Italian geology emphasize the importance of these distinct, pre-Numidian successions in defining tectonostratigraphic domains, and assume particular arrangements for their palaeogeographical disposition during Numidian deposition and in reconstructing tectonic displacements in the southern Apennines and Sicily. For example, the designation in Sicily of 'internal Numidian' and 'external Numidian' by Guerrera *et al.* (2012) and many others relies exclusively on characterizing their immediate

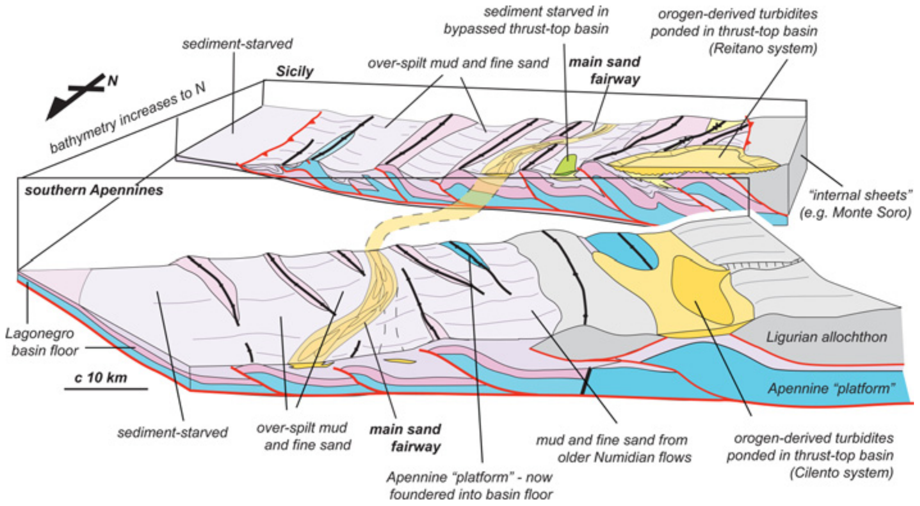

Fig. 13. Schematic representation of the Numidian turbidite system in Sicily and the southern Apennines. Thrust systems provided sinuous corridors that act to confine, but not contain, the causative turbidity currents for the Numidian, effectively fractionating highly elongate sand fairways from finer-grained sediment fractions. Coarse, amalgamated sandstones are inferred to have been deposited in distinct bar-form patches, elongated along the sand fairways. The thrust system also ponded relatively immature orogen-sourced sediment into thrust-top basins. These turbidites are inferred to have been both confined and contained, in the sense of Southern *et al.* (2015).

substrata. As noted elsewhere, deposition of Numidian turbidites upon rocks deposited originally on the carbonate platform (the so-called Panormide units) of Sicily requires this former platform to have experienced substantial subsidence prior to Miocene times. Thus, the definition of palaeogeographical domains such as platforms and basins, defined by Mesozoic strata, is an unreliable guide to basin geometry in the Miocene (Butler *et al.* 2019). The same deduction arises from accounts of the southern Apennines. Not only do Numidian turbidites overlie Flysch Rosso of the Lagonegro basin but, by including the Bifurto Formation within the Numidian system, also shallow-water Mesozoic carbonates (e.g. Fornelli *et al.* 2019). These are generally conflated into the contiguous Alburno–Cervati–Pollino platform (e.g. Iannace *et al.* 2005, and references therein; otherwise termed the Apennine Platform). However, for the causative flows of these far-transported Numidian sands to reach these substrates of the southern Apennines they must have crossed the Sicilian system together with the intervening basin. The southern Apennine Numidian would have deposited in deeper water than these up-system locations. Clearly then, the Apennine 'platform' was not a platform during the Langhian; indeed, it lay at greater bathymetries than the Argille Varicolori of central Sicily. This implies that, notwithstanding Miocene thrusting, the Mesozoic array of platforms and basins of this part of Tethys were significantly restructured, with new palaeogeographical juxtapositions presumably at some time in the early Tertiary.

A palaeogeographical sketch

The confined nature of the Numidian turbidites can be traced across both Sicily and the southern Apennines. In neither case did the turbidity currents, as recorded by the deposits discussed here, enter an unstructured foredeep or a broader deep-marine basin. We infer therefore that thrust systems provided structural continuity between the Maghrebian system of north Africa and Sicily and the southern Apennines (Fig. 14). The Numidian turbidity currents that reached the southern Apennines must have passed along the fairways in Sicily. Therefore, bathymetry increased from SW to NE around the thrust belt. During the Langhian the strata of the southern Apennines lay under deeper water than the thrust system of Sicily.

A challenge remains in defining the required confining slope to the SE of this thrust belt, such that turbidity currents from the Numidian system did not break out into the Ionian Sea basin (hence the question mark in Fig. 14). This inferred confining feature lies within what we refer to here as the 'Calabrian Gap'. Most existing palaeogeographical reconstructions depict the Calabrian Gap as

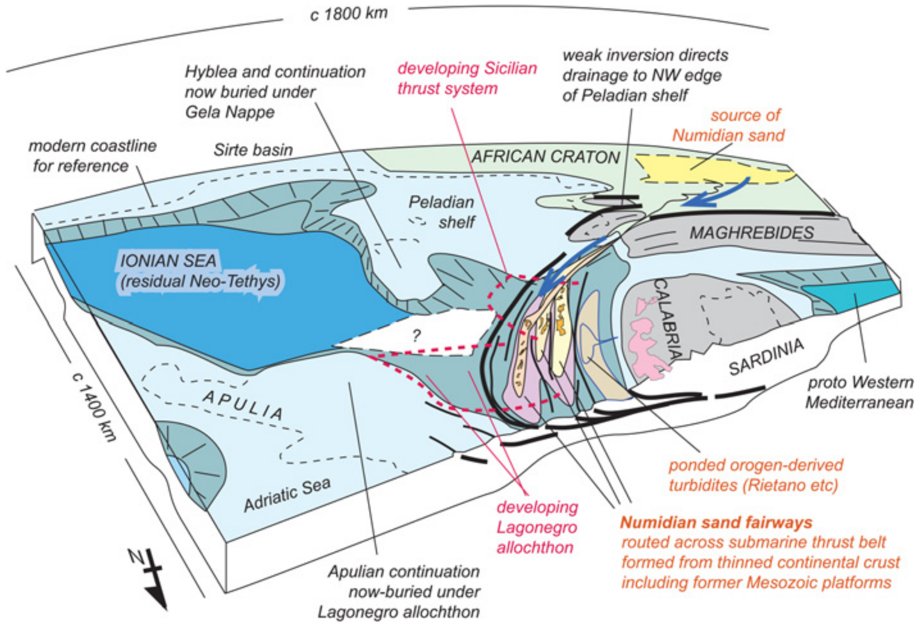

Fig. 14. Regional model for the continuity of the Numidian depositional system, routed across a thrust system connecting the southern Apennines, through Sicily into the Maghrebian orogen of north Africa.

containing an arm of the Tethyan ocean floor projecting westwards from the site of the modern Ionian Sea (e.g. Fig. 2a), separating the two orogenic foreland blocks of Hyblea and Apulia (Fig. 3b and c). Notwithstanding its widespread adoption in palaeogeographical reconstructions for the central Mediterranean, it seems unlikely that such a continuous seaway existed, certainly during the Langhian, or presumably the Numidian flows would have navigated a pathway through the structured seabed to this bathymetric low.

A variety of palaeogeographical reconstructions can satisfy the requirement for a confining slope to the SE of the Numidian sand fairway to fill the Calabrian Gap between Sicily and the southern Q10 Apennines. Le Breton *et al.* (2017) suggested that Hyblea and Apulia were in close proximity at 20 Ma and that the two blocks have separated as Apulia experienced a counter-clockwise rotation and convergence with the eastern side of the Adriatic Sea (Dinarides). Restoration of this displacement closes the Calabrian Gap. The confining slope to the Numidian system is provided by a near continuous platform and associated NW-facing slope. It is the subsequent rotation of Apulia and its divergence from Hyblea that opened the Calabrian Gap for the Calabria arc to migrate southeastwards into the Ionian basin. However, this model requires substantial right-lateral displacements to cut the Ionian basin and would be expected to offset the escarpment that now defines the SW edge of the Apulian platform and Adriatic Sea. No such structure has been recognized (e.g. Catalano *et al.* 2001). It seems most likely that Hyblea and Apulia have remained in the same relative position, at least since the Mesozoic.

Rather than displace Apulia relative to Hyblea, the Calabrian Gap may instead have been filled by the continuation of continental crust from these two blocks, much of which now lies buried and partially telescoped by the southern Apennine and Sicilian thrust systems. In this model the western limit of Ionian Tethys coincided with the modern Malta escarpment. That there has been continuity between Apulia and the Mesozoic carbonate platforms of the southern Apennines and continental north Africa is strongly indicated by the dispersal of terrestrial megafauna during the late Cretaceous (e.g. Zarcone *et al.* 2010).

A third alternative, and our preferred model, for filling the Calabrian Gap is to invoke a submarine thrust belt largely occluding the deep basin lying on Ionian oceanic crust (Fig. 14). The challenge with this model is to create a scenario where Numidian turbidites are entirely restricted to lie on the thrust belt. Their flows cannot have breached the thrust belt and accessed the deep ocean basin that would have lain ahead of it.

One remaining challenge facing our model for a structurally confined Numidian turbidite system lies in accounting for the volumes of finer-grained sediment that is presumed to have been carried over the coarser grain fractions through flow bypass. Earlier flows that deposited their coarse sand in Sicily could of course have carried their finer sand and mud into what is now the southern Apennines. However, the significant bypassed sediment inferred here to have been associated with the coarser fractions of the southern Apennines has no obvious down-system continuation within which it might have accumulated. One possibility is that the distal flows broke out of their thrust-top confinement to enter a true foredeep. In Sicily, for example, the more forelandward stratigraphic sections are dominated by mud and very fine sands (Fig. 5, column E). Although some of this material may represent lateral overspill from confined flows on the thrust belt, it is possible that some may also represent distal deposits from older flows.

A modern analogue for the palaeogeography proposed here for the central Mediterranean during early Miocene times lies in the SW Caribbean. Drainage from South America enters the Caribbean at the Gulf of Uraba and encounters a seabed structured by folds of the North Panama Thrust Belt (e.g. Silver *et al.* 1990). Thrust-top basins (e.g. the San Bias basin) are trapping at least part of the detritus being shed from the rising Panama orogen. Other examples could include the NW Arafura Sea, where the eastern part of the Banda arc impinges on western Papua, Indonesia.

Turbidites as tectonic tracers

The central tenets of our paper are that turbidites, as the products of subaqueous gravity flows, can map out bathymetric lows, and that their sedimentology may be used to infer the shape of the basins within which they are contained. Our work is consistent with other studies indicating that structurally confined but uncontained turbidite systems leave sand-rich fairways comprising stacked bed-sets (e.g. Liu *et al.* 2018; Casciano *et al.* 2019). These turbidite sand fairways reflect not only the connectivity between arrays of basins but also the relative elevation of parts of the basin floor. These are first-order elements that can be used to infer palaeogeography, especially charting parts of the history of vertical movement, in our case study, of the complex array of blocks and basins that have become incorporated into the Maghrebian–Apennine orogenic system. That coarse sand has been carried a long distance across the basins requires the causative turbidity currents to maintain their capacity to carry sediment, a deduction reinforced by the presence of large grains in the more distal deposits together with distinct grain-size breaks throughout (indicative of flow-stripping and bypass; Stevenson *et al.* 2015). This behaviour is characteristic of deposits from flows that were confined laterally. In the absence of autogenic channel–levee complexes, turbidites with these characteristics presumably reflect confinement by basin structures.

A key assumption in our analysis has been that the sand and coarse grain-size fractions within the Numidian turbidites have been derived from north Africa. This could be invalidated if the causative flows entrained sand from older successions that originally lay in their paths. However, for the Numidian system in Sicily and the southern Apennines, its substrate is represented by carbonates with their associated mudstones. There are no significant coarse siliciclastic successions from which quartz sand might have been entrained. Therefore, the Numidian sediment effectively acts as a tracer or dye, uncontaminated from its north African source, that tracks turbidity currents down-system. This is an important constraint. For our approach to be applied elsewhere, turbidite systems should be chosen that represent an early influx of siliciclastic material into an array of basins that otherwise, and previously, were starved of such sediment compositions. In orogenic systems, especially those of the western Tethys, where carbonate deposition dominated much of the Mesozoic, it is the earlier synorogenic strata that may prove the most amenable to our approach.

Conclusions

Coarse-grained quartz sandstones of the Numidian turbidite system (Burdigalian–Langhian in age) are found in Sicily and the southern Apennines of mainland Italy. These outcrops have been carried on tectonic allochthons and partially dismembered by rotational thrusting through the later Miocene and Pliocene. When these displacements are reconstructed, the Numidian sandstone defines a composite fairway that can be traced for over 300 km.

Both in Sicily and the southern Apennines, the Numidian sandstones have abrupt bed tops that show distinct grain-size breaks. The deposits include quartz pebbles and lags. This suggests not only that the capacity of the causative turbidity currents to carry coarse sand and bed-load was maintained for many hundreds of kilometres down-system but also that much of the flow bypassed the seabed. Flow bypass on this scale strongly suggests that the turbidity currents were confined (e.g. Stephenson *et al.* 2015). Our previous Q11 work in Sicily (Pinter *et al.* 2016, 2018) indicates that confinement was provided by active folding associated with the Maghrebian thrust belt.

We conclude that the Numidian turbidites were deposited in structurally controlled tortuous corridors, developed along synforms associated with a submarine thrust system, and that the Numidian turbidity currents flowed across an evolving tectonic allochthon (see also Butler *et al.* 2019). Structural evolution will have influenced the path taken by the flows, an inference consistent with the system's biostratigraphy for Sicily (Pinter *et al.* 2016, 2018). This shows diachronous migration of the main sand fairways through the Burdigalian and Langhian.

The Numidian turbidity currents were fed axially, derived from the SW corner of the thrust belt. The southern Apennine outcrops of Numidian sandstone show the same sedimentary characteristics as their Sicilian counterparts. Therefore, the thrust system and its bathymetric relief was continuous, from the main Maghrebian chains of northern Africa into the Apennine chain. Presumably the Langhian-aged sandstones of the southern Apennines were deposited by flows that bypassed through the sand fairways of that age in Sicily. Bathymetry increased anticlockwise around the thrust system. It is unlikely that there was deep bathymetric connection between this arcuate thrust system and the Ionian Sea basin to the SE. Certainly, by Burdigalian and Langhian times, any residual arm of the Tethyan ocean through this region had effectively closed.

The Numidian sandstones stratigraphically overlie various substrata representative of different Mesozoic palaeogeographical units (Butler *et al.* 2019, and references therein). For example, Numidian turbidites locally overlie Mesozoic rocks in platform facies in the southern Apennines but the causative turbidity currents from which these sandstones were deposited must have transited through the sand fairways in Sicily, and these lie on apparently deep-marine strata (Argille Varicolori Formation). This implies significant restructuring of the Mesozoic palaeogeographical framework. The Mesozoic units are not, of themselves, indicative of the palaeogeography of blocks and basins in the central Mediterranean, certainly during the Miocene and probably through the early Tertiary.

Stratigraphy has long been used to inform palaeogeographical reconstructions. The Numidian case study developed here illustrates the utility of using the sedimentology of turbidites to gain understanding of basin structure that can inform palaeogeographical models on the scale of hundreds of kilometres. Our study benefits from using strata with distinctive sediment compositions, in this case hyper-mature quartz sand derived from north Africa that entered a seaway floored by carbonates, claystones, mudstones and marls. The distinct provenance reduces possible confusion with other, orogen-derived, more locally sourced turbidites. The approach is therefore most applicable to understanding systems using the first siliciclastic clastic inputs into otherwise sediment-restricted marine basins.

Acknowledgements Key elements of our work were presented at the conference on 'Deep-water depositional systems: advances and applications' held at the Geological Society in 2017. We thank participants for discussions and apologize for the tardy preparation of this work. We are also indebted to two deceased colleagues at the University of Catania who supported our research endeavours over the years and generously discussed Sicilian and southern Apennine geology on numerous occasions: Mario Grasso and Fabio Lentini. M. Patacci and N. Lentsch are thanked for insightful reviews. However, of course, the authors are solely responsible for the interpretations presented here.

Funding The research presented here was funded by BG-Shell in partnership with CNPq-Brazil (National Council for Scientific and Technological Development). R.M. acknowledges a Piano Triennale della Ricerca 2016-2018 grant awarded from the University of Catania. Q12

Author contributions **RWHB**: conceptualization (lead), formal analysis (equal), funding acquisition (equal), investigation (equal), methodology (equal), project administration (lead), supervision (lead), writing – original draft (lead), writing – review & editing (equal); **PRP**: formal analysis (equal), investigation (equal), methodology (equal), writing – review & editing (supporting); **RM**: formal analysis (equal), investigation (equal), methodology (equal), writing – review & editing (equal); **AJH**: conceptualization (supporting), formal analysis (supporting), funding acquisition (equal), investigation (supporting), methodology (supporting), supervision (equal), writing – review & editing (supporting)

Scientific editing by Linda Kirstein

References

Accaino, F., Catalano, R. *et al.* 2011. A crustal seismic profile across Sicily. *Tectonophysics*, **508**, 52–61, https://doi.org/10.1016/j.tecto.2010.07.011 Q13

Albertão, G.A., Eschard, R., Mulder, T., Teles, V., Chauveau, B. and Joseph, P. 2015. Modeling the deposition of turbidite systems with Cellular Automata numerical simulations: A case study in the Brazilian offshore. *Marine and Petroleum Geology*, **59**, 166–186, https://doi.org/10.1016/j.marpetgeo.2014.07.010

Aldega, L., Corrado, S., Di Paolo, L., Somma, R., Maniscalco, R. and Balestrieri, M.L. 2011. Shallow burial and exhumation of the Peloritani Mountains (NE Sicily, Italy): Insight from paleothermal and structural indicators. *Geological Society of America Bulletin*, **123**, 132–149, https://doi.org/10.1130/B30093.1

Baas, J.H., Best, J.L. and Peakall, J. 2011. Depositional processes, bedform development and hybrid bed formation in rapidly decelerated cohesive (mud–sand) sediment flows. Sedimentology. *Sedimentology*, **58**, 1953–1987, https://doi.org/10.1111/j.1365-3091.2011.01247.x

Balogh, K., Cassola, P., Pompilio, M. and Puglisi, D. 2001. Petrographic, geochemical and radiometric data on Tertiary volcano-arenitic beds from the Sicilian Maghrebian Chain: volcanic sources and geodynamic implications. *Geologica Carpathica*, **52**, 15–21. Q14

Barreca, G. and Monaco, C. 2013. Vertical-axis rotations in the Sicilian fold and thrust belt: new structural constraints from the Madonie Mts. (Sicily, Italy). *Italian Journal of Geosciences*, **132**, 407–421, https://doi.org/10.3301/IJG.2012.44

Bianchi, F., Carbone, S. *et al.* 1987. Sicilia Orientale: profilo geologico Nebrodi-Iblei. *Memorie della Società Geologica Italiana*, **38**, 429–458.

Boenzi, F., Ciaranfi, N. and Pieri, P. 1968. Osservazioni geologiche nei dintorni di Accettura e di Oliveto Lucano. *Memorie della Società Geologica Italiana*, **7**, 379–392.

Bonardi, G., Giunta, G., Perrone, V., Russo, M., Zuppetta, A. and Ciampo, G. 1980. Osservazioni sull'evoluzione miocenica dell'Arco Calabro-Peloritano nel Miocene Inferiore: la Formazione di Stilo–Capo d'Orlando. *Bollettino della Società Geologica Italiana*, **99**, 365–393.

Bouma, A. 1962. *Sedimentology of some flysch deposits. A graphic approach to facies interpretation*. Elsevier, Amsterdam.

Bouma, A.H. and Ravenne, C. 2004. The Bouma Sequence (1962) and the resurgence of geological interest in the French Maritime Alps (1980s): the influence of the Grès d'Annot in developing ideas of turbidite systems. Geological Society, London, Special Publications, **221**, 27–38, https://doi.org/10.1144/GSL.SP.2004.221.01.03

Butler, R.W.H., Maniscalco, R. and Pinter, P. 2019. Syn-kinematic sedimentary systems as constraints on the structural response of thrust belts: re-examining the structural style of the Maghrebian thrust belt of Eastern Sicily. *Italian Journal of Geosciences*, **138**, 371–389, https://doi.org/10.3301/IJG.2019.11

Cammarosano, A., Cavuoto, G. *et al.* 2004. Nuovi dati e nuove interpretazioni sui flysch terrigeni del Cilento (Appennino meridionale, Italia). *Bollettino della Società Geologica Italiana*, **119**, 395–405.

Carbone *et al.* 1987 (details to be added by author).

Casciano, C.I., Patacci, M., Longhitano, S.G., Tropeano, M., McCaffrey, W.D. and Di Celma, C. 2019. Multi-scale analysis of a migrating submarine channel system in a tectonically-confined basin: The Miocene Gorgoglione Flysch Formation, southern Italy. *Sedimentology*, **66**, 205–240, https://doi.org/10.1111/sed.12490

Cassola, P., Costa, E., Loiacono, F., Moretti, E., Morlotti, E., Puglisi, D. and Villa, G. 1992. New sedimentologic, petrographic, biostratigraphic and structural data on the Reitano Flysch (Maghrebian Chain, Sicily). *Rivista Italiana di Paleontologia e Stratigrafia*, **98**, 205–228. Q15

Cassola, P., Loiacono, F., Moretti, E., Nigro, F., Puglisi, D. and Sbarra, R. 1995. Sedimentology, petrography and structure of the Reitano Flysch in the northern sector of the Nebrodi Mountains (NE Sicily). *Giornale di Geologia*, **57**, 195–121. Q16

Catalano, R., Doglioni, C. and Merlini, S. 2001. On the Mesozoic Ionian Basin. *Geophysical Journal International*, **144**, 49–64, https://doi.org/10.1046/j.0956-540X.2000.01287.x

Cavuoto, G., Martelli, L., Nardi, G. and Valente, A. 2004. Depositional systems and architecture of Oligo-Miocene turbidite successions in Cilento (Southern Apennines). *GeoActa*, **3**, 129–147.

Cavuoto, G., Martelli, L., Nardi, G. and Valente, A. 2007. Turbidite depositional systems and architectures, Cilento, Italy. AAPG, Studies in Geology, **56**, CD-ROM.

Cesarano, M., Pierantoni, P.P. and Turco, E. 2002. Structural analysis of the Albidona Formation in the Alessandria del Carretto–Plataci area (Calabro-Lucanian Apennines, southern Italy). *Bollettino della Società Geologica Italiana, Special Issue*, **1**, 669–676.

Civile, D., Lodolo, E., Caffau, M., Baradello, L. and Ben-Avraham, Z. 2016. Anatomy of a submerged archipelago in the Sicilian Channel (central Mediterranean Sea). *Geological Magazine*, **153**, 160–178, https://doi.org/10.1017/S0016756815000485 **Q17**

Critelli, S. 1991. Evoluzione delle mode detritiche delle successioni arenitiche terziarie dell'Apennino Meridionale. *Memorie della Società Geologica Italiana*, **47**, 55–93. **Q18**

Critelli, S. 1999. The interplay of lithospheric flexure and thrust accommodation in forming stratigraphic sequences in the southern Apennines foreland basin system, Italy. *Rendiconti di Fisica Accademia dei Lincei*, **10**, 257–326, https://doi.org/10.1007/BF02904390

Critelli, S. 2018. Provenance of Mesozoic to Cenozoic circum-Mediterranean sandstones in relation to tectonic setting. *Earth-Science Reviews*, **185**, 624–648, https://doi.org/10.1016/j.earscirev.2018.07.001

Critelli, S., Muto, F., Perri, F. and Tripodi, V. 2017. Interpreting provenance relations from sandstone detrital modes, southern Italy foreland region: Stratigraphic record of the Miocene tectonic evolution. *Marine and Petroleum Geology*, **87**, 47–59, https://doi.org/10.1016/j.marpetgeo.2017.01.026

Critelli *et al.* 2018 (details to be added by author).

de Capoa, P., Guerrera, F., Perrone, V., Serrano, F. and Tramontana, M. 2000. The onset of the syn-orogenic sedimentation in the Flysch Basin of the Sicilian Maghrebids: state of the art and new biostratigraphic constraints. *Eclogae Geologicae Helvetiae*, **93**, 65–79. **Q19**

de Capoa, P., Di Staso, A., Guerrera, F., Perrone, V., Tramontana, M. and Zaghloul, M.N. 2002. The Lower Miocene volcaniclastic sedimentation in the Sicilian sector of the Maghrebian Flysch Basin: geodynamic implications. *Geodinamica Acta*, **15**, 141–157, https://doi.org/10.1080/09853111.2002.10510747 **Q20**

de Capoa, P., Di Staso, A., Guerrera, F., Perrone, V. and Tramontana, M. 2004. The age of the oceanic accretionary wedge and onset of continental collision in the Sicilian Maghrebian Chain. *Geodinamica Acta*, **17**, 331–348, https://doi.org/10.3166/ga.17.331-348 **Q21**

de Capoa *et al.* 2012 (details to be added by author).

de Leeuw, J., Eggenhuisen, J.T. and Cartigny, M.J.B. 2018. Linking submarine channel–levee facies and architecture to flow structure of turbidity currents: insights from flume tank experiments. *Sedimentology*, **65**, 931–951, https://doi.org/10.1111/sed.12411

d'Errico, M., Di Staso, A., Fornelli, A., Guida, D., Micheletti, F., Perrone, V. and Raffaelli, G. 2014. The Numidian Flysch: a guide formation for the reconstruction of the paleogeography and tectono-sedimentary evolution of southern Apennines. *Bulletin de la Société Géologique de France*, **185**, 343–356, https://doi.org/10.2113/gssgfbull.185.5.343

Dewever *et al.* 2010 (details to be added by author).

Elter, P., Grasso, M., Parotto, M. and Vezzani, L. 2003. Structural setting of the Apennine–Maghrebian thrust belt. *Episodes*, **26**, 205–211, https://doi.org/10.18814/epiiugs/2003/v26i3/009

Finetti, I.R., Lentini, F. *et al.* 2005. Geological outline of Sicily and lithospheric tectono-dynamics of its Tyrrhenian margin from new CROP seismic data. *In*: Finetti, I.R. (ed.) *CROP Project: deep seismic exploration of the central Mediterranean and Italy*. Elsevier, Amsterdam, 319–375.

Fornelli, A., Micheletti, F., Langone, A. and Perrone, V. 2015. First U–Pb detrital zircon ages from Numidian sandstone in southern Apennines: evidences of African provenance. *Sedimentary Geology*, **320**, 19–29, https://doi.org/10.1016/j.sedgeo.2015.02.005

Fornelli, A., Gallicchio, S. and Micheletti, F. 2019. U–Pb detrital zircon ages and compositional features of Bifurto quartz-rich sandstones from Southern Apennines (Southern Italy): comparison with Numidian Flysch sandstones to infer source area. *Italian Journal of Geosciences*, **138**, 216–230, https://doi.org/10.3301/IJG.2019.02

Gamberi, F. and Rovere, M. 2011. Architecture of a modern transient slope fan (Villafranca fan, Gioia basin—Southeastern Tyrrhenian Sea). *Sedimentary Geology*, **236**, 211–225, https://doi.org/10.1016/j.sedgeo.2011.01.007

Gandolfi, G., Paganelli, L. and Zuffa, G.G. 1983. Petrology and dispersal directions in the Marnoso Arenacea Formation (Miocene, northern Apennines). *Journal of Sedimentary Petrology*, **53**, 493–507.

Grasso, M., Lickorish, W.H. *et al.* 1997. *Geological map of the Licata fold belt (south–central Sicily)*. Società Elaborazioni Cartografiche, Firenze.

Grasso, M., Aiello, A. and Romeo, M. 1999. Età e posizione strutturale del "Flysch" di Reitano affiorante presso Cerami (Monti Nebrodi), Sicilia Centro-Settentrionale. *Bolletino della Accademia Gioenia di Scienze Naturali Catania*, **31**, 211–223.

Guerrera, F., Martin-Martin, M., Perrone, V. and Tramontana, M. 2005. Tectono-sedimentary evolution of the southern branch of the western Tethys (Maghrebian Flysch Basin and Lucanian ocean): Consequences for western Mediterranean geodynamics. *Terra Nova*, **17**, 358–367, https://doi.org/10.1111/j.1365-3121.2005.00621.x

Guerrera, F., Martín-Algarra, A. and Martín Martín, M. 2012. Tectono-sedimentary evolution of the "Numidian Formation" and lateral facies (southern branch of the western Tethys): Constraints for central–western Mediterranean geodynamics. *Terra Nova*, **24**, 34–41, https://doi.org/10.1111/j.1365-3121.2011.01034.x

Handy, M.R., Schmid, S.M., Bousquet, R., Kissling, E. and Bernoulli, D. 2010. Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps. *Earth-Science Reviews*, **102**, 121–158, https://doi.org/10.1016/j.earscirev.2010.06.002

Haughton, P., Davis, C., McCaffrey, W. and Barker, S. 2009. Hybrid sediment gravity flow deposits – Classification, origin and significance. *Marine and Petroleum Geology*, **26**, 1900–1918, https://doi.org/10.1016/j.marpetgeo.2009.02.012

Hu, X., Garzanti, E., Wang, J.G., Huang, W., An, W. and Webb, A. 2016. The timing of India–Asia collision onset – Facts, theories, controversies. *Earth-Science Reviews*, **160**, 264–299, https://doi.org/10.1016/j.earscirev.2016.07.014

Iannace, A., Bonardi, G., D'Errico, M., Mazzoli, S., Perrone, V. and Vitale, S. 2005. Structural setting and tectonic evolution of the Apennine Units of northern Calabria. *Comptes Rendus Géoscience*, **337**, 1541–1550, https://doi.org/10.1016/j.crte.2005.09.003

Johansson, M., Braakenburg, N.E., Stow, D.A.V. and Faugères, J.C. 1998. Deep-water massive sands: facies, processes and channel geometry in the Numidian Flysch, Sicily. *Sedimentary Geology*, **115**, 233–265, https://doi.org/10.1016/S0037-0738(97)00095-X

Joseph, P. and Lomas, S.A. (eds) 2004. *Deep-water sedimentation in the Alpine Basin of SE France: new perspectives on the Grès d'Annot and related systems*. Geological Society, London, Special Publications, **221**, https://doi.org/10.1144/GSL.SP.2004.221.01.01

Kane, I.A., Pontén, A.S., Vangdal, B., Eggenhuisen, J.T., Hodgson, D.M. and Spychala, Y.T. 2017. The stratigraphic record and processes of turbidity current transformation across deep-marine lobes. *Sedimentology*, **64**, 1236–1273, https://doi.org/10.1111/sed.12346

Kneller, B.C. and McCaffrey, W.D. 2003. The interpretation of vertical sequences in turbidite beds: the influence of longitudinal flow structure. *Journal of Sedimentary Research*, **73**, 706–713, https://doi.org/10.1306/031103730706

Le Breton, E., Handy, M.R., Molli, G. and Ustaszewski, K. 2017. Post-20 Ma motion of the Adriatic Plate: New constraints from surrounding orogens and implications for crust–mantle decoupling. *Tectonics*, **36**, 3135–3154, https://doi.org/10.1002/2016TC004443

Lentini, F. 1982. The geology of the Mount Etna basement. Memorie della Società Geologica Italiana, **23**, 7–25.

Lentini and Carbone 2012 (details to be added by author).

Lentini, F. and Carbone, S. 2014. *Carta geologica della Sicilia (1:250,000)*. Società Elaborazioni Cartografiche, Firenze.

Lentini, F., Carbone, S., Di Stefano, A. and Guarnieri, P. 2002. Stratigraphical and structural constraints in the Lucanian Apennines (southern Italy): tools for reconstructing the geological evolution. *Journal of Geodynamics*, **34**, 141–158, https://doi.org/10.1016/S0264-3707(02)00031-5

Liu, Q., Kneller, B., Fallgatter, C., Valdez Buso, V. and Milana, J.P. 2018. Tabularity of individual turbidite beds controlled by flow efficiency and degree of confinement. *Sedimentology*, **65**, 2368–2387, https://doi.org/10.1111/sed.12470

Lucente, C., Margheriti, L., Piromallo, C. and Barroul, G. 2006. Seismic anisotropy reveals the long route of the slab through the western–central Mediterranean mantle. *Earth and Planetary Science Letters*, **241**, 517–529, https://doi.org/10.1016/j.epsl.2005.10.041

Martin, A.K. 2006. Oppositely directed pairs of propagating rifts in backarc basins: double saloon door sea floor spreading during subduction rollback. *Tectonics*, **25**, TC3008, https://doi.org/10.1029/2005TC001885

Mazzoli, S., Aldega, L., Corrado, S., Invernizzi, C. and Zattin, M. 2006. Pliocene–Quaternary thrusting, syn-orogenic extension and tectonic exhumation in the Southern Apennines (Italy): Insights from the Monte Alpi area. Geological Society of America, Special Papers, **414**, 55–77.

Meiburg, M.E. and Kneller, B.C. 2010. Turbidity currents and their deposits. *Annual Review of Fluid Mechanics*, **42**, 135–156, https://doi.org/10.1146/annurev-fluid-121108-145618

Meschede, M. and Frische, W. 1998. A plate-tectonic model for the Mesozoic and Early Cenozoic history of the Caribbean plate. *Tectonophysics*, **296**, 269–291, https://doi.org/10.1016/S0040-1951(98)00157-7

Meulenkamp, J.E. and Sissingh, W. 2003. Tertiary palaeogeography and tectonostratigraphic evolution of the Northern and Southern Peri-Tethys platforms and the intermediate domains of the African–Eurasian convergent plate boundary zone. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **196**, 209–228, https://doi.org/10.1016/S0031-0182(03)00319-5

Meulenkamp et al. 2003 (details to be added by author).

Monaco, C. and de Guidi, G. 2006. Structural evidence for Neogene rotations in the eastern Sicilian fold and thrust belt. *Journal of Structural Geology*, **28**, 561–574, https://doi.org/10.1016/j.jsg.2006.01.010

Mongelli, G. 2004. Rare-earth elements in Oligo-Miocenic pelitic sediments from Lagonegro Basin, southern Apennines, Italy: implications for provenance and source area weathering. *International Journal of Earth Sciences*, **93**, 612–620, https://doi.org/10.1007/s00531-004-0401-z

Müller, R.D., Seton, M. *et al.* 2016. Ocean basin evolution and global-scale plate reorganization events since Pangea breakup. *Annual Review of Earth and Planetary Science*, **44**, 107–138, https://doi.org/10.1146/annurev-earth-060115-012211

Mutti, E. 1992. *Turbidite Sandstones*. AGIP–Istituto di Geologia, Università di Parma, Parma.

Mutti, E. and Ricci Lucchi, F. 1978. Turbidites of the northern Apennines: introduction to facies analysis. *International Geology Review*, **20**, 125–166, https://doi.org/10.1080/00206817809471524

Mutti, E., Bernoulli, D., Lucchi, F.R. and Tinterri, R. 2009. Turbidites and turbidity currents from alpine "flysch" to the exploration of continental margins. *Sedimentology*, **56**, 267–318, https://doi.org/10.1111/j.1365-3091.2008.01019.x

Ogniben, L. 1960. Nota illustrativa dello schema geologico della Sicilia nord-orientale. *Rivista Mineraria Siciliana*, **11**, 184–212.

Parize, O., Beaudoin, B., Burollet, P.F., Cojan, G.F. and Pinault, M. 1986. La provenance du materiel gréseux numidien est septentrionale (Sicilie et Tunisie). *Comptes Rendus de l'Académie des Sciences*, **288**, 1671–1674.

Patacca, E., Scandone, P., Bellatalla, M., Perilli, N. and Santini, U. 1992. The Numidian-sand event in the Southern Apennines. *Memorie di Scienze Geologiche dell'Università di Padova*, **43**, 297–337.

Patacci, M., Haughton, P.D. and McCaffrey, W.D. 2015. Flow behavior of ponded turbidity currents. *Journal of Sedimentary Research*, **85**, 885–902, https://doi.org/10.2110/jsr.2015.59

Q22 Patacci, M., Marini, M., Felletti, F., Di Giulio, A., Setti, M. and McCaffrey, W. 2020. Origin of mud in turbidites and hybrid event beds: Insight from ponded mudstone caps of the Castagnola turbidite system (north-west Italy). *Sedimentology*, https://doi.org/10.1111/sed.12713

Pedley, H.M. 1981. Sedimentology and palaeoenvironment of the southeast Sicilian Tertiary platform carbonates. *Sedimentary Geology*, **28**, 273–291, https://doi.org/10.1016/0037-0738(81)90050-6 Q23

Pickering, K.T. and Hiscott, R.N. 2016. *Deep Marine Systems: Processes, Deposits, Environments, Tectonics and Sedimentation*. Wiley, Chichester.

Pinter, P.R., Butler, R.W.H., Hartley, A.J., Maniscalco, R., Baldassini, N. and Di Stefano, A. 2016. The Numidian of Sicily revisited: A thrust-influenced confined turbidite system. *Marine and Petroleum Geology*, **78**, 291–311, https://doi.org/10.1016/j.marpetgeo.2016.09.014

Pinter, P.R., Butler, R.W.H., Hartley, A.J., Maniscalco, R., Baldassini, N. and Di Stefano, A. 2018. Tracking sand fairways through a deformed turbidite system: the Numidian (Miocene) of Central–East Sicily, Italy. *Basin Research*, **30**, 480–501, https://doi.org/10.1111/bre.12261

Puglisi, D. 2014. Tectonic evolution of the Sicilian Maghrebian Chain inferred from stratigraphic and petrographic evidences of Lower Cretaceous and Oligocene flysch. *Geologica Carpathica*, **65**, 293–305, https://doi.org/10.2478/geoca-2014-0020

Reading, H.G. and Richards, M. 1994. Turbidite systems in deep-water basin margins classified by grain size and feeder system. *AAPG Bulletin*, **78**, 792–822.

Rowley, D.B. 1996. Age of initiation of collision between India and Asia: A review of stratigraphic data. *Earth and Planetary Science Letters*, **145**, 1–13, https://doi.org/10.1016/S0012-821X(96)00201-4

Selli, R. 1957. Sulla trasgressione del Miocene in Italia meridionale. *Giornale di Geologia*, **24**, 1–54.

Selli, R. 1962. Il Paleogene nel quadro della geologia dell'Italia centro-meridionale. *Memorie della Società Geologica Italiana*, **3**, 737–789.

Shanmugam, G. 2016. Submarine fans: a critical retrospective (1950–2015). *Journal of Palaeogeography*, **5**, 110–184, https://doi.org/10.1016/j.jop.2015.08.011

Silver, E.A., Reed, D.L., Tagudin, J.E. and Heil, D.J. 1990. Implications of the north and south Panama thrust belts for the origin of the Panama Orocline. *Tectonics*, **9**, 261–281, https://doi.org/10.1029/TC009i002p00261

Sohn, Y.K. 1997. On traction-carpet sedimentation. *Journal of Sedimentary Research*, **67**, 502–509, https://doi.org/10.1306/D42685AE-2B26-11D7-8648000102C1865D

Southern, S.J., Patacci, M., Felletti, F. and McCaffrey, W.D. 2015. Influence of flow containment and substrate entrainment upon sandy hybrid event beds containing a co-genetic mud-clast-rich division. *Sedimentary Geology*, **321**, 105–122, https://doi.org/10.1016/j.sedgeo.2015.03.006

Speranza, F., Maniscalco, R. and Grasso, M. 2003. Pattern of orogenic rotations in central–eastern Sicily: implications for the timing of spreading in the Tyrrhenian Sea. *Journal of the Geological Society, London*, **160**, 183–195, https://doi.org/10.1144/0016-764902-043

Speranza *et al.* 2012 (details to be added by author).

Stampfli, G.M. and Borel, G.D. 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth and Planetary Science Letters*, **196**, 17–33, https://doi.org/10.1016/S0012-821X(01)00588-X

Stephenson *et al.* 2015 (details to be added by author).

Stevenson, C.J., Talling, P.J. *et al.* 2013. The flows that left no trace: Very large-volume turbidity currents that bypassed sediment through submarine channels without eroding the sea floor. *Marine and Petroleum Geology*, **41**, 186–205, https://doi.org/10.1016/j.marpetgeo.2012.02.008

Stevenson, C.J., Jackson, C.A., Hodgson, D.M., Hubbard, S.M. and Eggenhuisen, J.T. 2015. Deep-water sediment bypass. *Journal of Sedimentary Research*, **85**, 1058–1081, https://doi.org/10.2110/jsr.2015.63

Stow, D.A. and Mayall, M. 2000. Deep-water sedimentary systems: new models for the 21st century. *Marine and Petroleum Geology*, **17**, 25–135, https://doi.org/10.1016/S0264-8172(99)00064-1

Thomas, M.F.H. and Bodin, S. 2013. Architecture and evolution of the Finale channel system, the Numidian Flysch Formation of Sicily; insights from a hierarchical approach. *Marine and Petroleum Geology*, **41**, 163–185, https://doi.org/10.1016/j.marpetgeo.2012.02.002

Thomas, M.F.H., Bodin, S., Redfern, J. and Irving, D.H.B. 2010. A constrained African craton source for the Cenozoic Numidian Flysch: implications for the palaeogeography of the western Mediterranean basin. *Earth-Science Reviews*, **101**, 1–23, https://doi.org/10.1016/j.earscirev.2010.03.003

Van Hinsbergen, D.J., Torsvik, T.H. *et al.* 2020. Orogenic architecture of the Mediterranean region and kinematic reconstruction of its tectonic evolution since the Triassic. *Gondwana Research*, **81**, 79–229, https://doi.org/10.1016/j.gr.2019.07.009

Von Hinsbergen *et al.* 2019 (details to be added by author).

von Hagke, C., Philippon, M., Avouac, J.-P. and Gurnis, M. 2016. Origin and time evolution of subduction polarity reversal from plate kinematics of Southeast Asia. *Geology*, **44**, 659–662, https://doi.org/10.1130/G37821.1

Wezel, F.C. 1970. Numidian flysch: an Oligocene–early Miocene continental rise deposit off the African platform. *Nature*, **228**, 275–276, https://doi.org/10.1038/228275a0

Zarcone, G., Petti, F.M., Cillari, A., Di Stefano, P., Guzzetta, D. and Nicosia, U. 2010. A possible bridge between Adria and Africa: new paleobiogeographic and stratigraphic constraints on the Mesozoic palaeogeography of the Central Mediterranean area. *Earth-Science Reviews*, **103**, 154–162, https://doi.org/10.1016/j.earscirev.2010.09.005

Zuppetta, A., Russo, M. and Mazzoli, S. 2004. Miocene tectonic evolution of the Southern Apennine thrust front (Italy): Stratigraphic and structural constraints from the eastern Calabria–Lucania borderland area. *Geodinamica Acta*, **17**, 141–151, https://doi.org/10.3166/ga.17.141-151