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Deep-water massive sands: facies, processes and channel geometry in the Numidian Flysch, Sicily

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Abstract

The sedimentology of the Numidian Flysch in northern Sicily has been little studied in the last twenty years, with most works concentrating on the structural complexities of the area, rather than the facies characteristics. The Numidian basin was intensively deformed during its complex tectonic history and the basin deposits have become segmented into different structural units. The Oligo–Miocene aged Flysch comprises predominantly quartzarenitic sandstones and interbedded mudstones, both of turbiditic affinities and most likely derived from a NW African source. The sediments are well exposed along the coast and in dry river valleys in northern Sicily, and provide excellent examples of *deep-water massive sands*, i.e. very thick (4–25 m) units of structureless sandstone associated with turbidites and related facies. The overall characteristics of the examined sections indicate that the sandstones were deposited within both isolated channels and larger channel complexes that fed across a mud-dominated slope. The more proximal sections, e.g. Ponte Finale and Pollina have a high proportion of pebble conglomerates, shale-clast conglomerates and very thick-bedded structureless pebbly sandstones, deposited by high-density turbidity currents, debris flows and slumping. Other sections, either more distal or with a more uniform sand-rich source, e.g. Contrada di Romano, are dominated by very thick-bedded and amalgamated structureless sandstones with extensive zones of water-escape structures. The massive sands are thought to originate from the gradual aggradation of sediment beneath steady or near-steady flows, with rapid deposition from final-stage modified grain flows forming the water-escape features. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: turbidites; massive sands; Numidian Flysch; Sicily

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1. Introduction

The Numidian Flysch Formation forms part of a complex late Cenozoic orogenic belt that stretches some 2000 km from mainland Italy (the southern Apennines and Calabrians), through northern Sicily, across northern Africa (the Maghrebides) and into southern Spain (Bouillin et al., 1986; Hoyez, 1989) (Fig. 1). The Numidian Flysch in northern Sicily is well-exposed and tends to be found either forming prominent cliff sections along the coast, flanking dry river valleys, or as high peaks and ridges. However, apart from several important papers dealing with structural and tectonic aspects of the Sicilian deposits (Benomran et al., 1987; Dewey et al., 1989; Hoyez, 1989; Roure et al., 1990), there has been very little published on the detailed sedimentology

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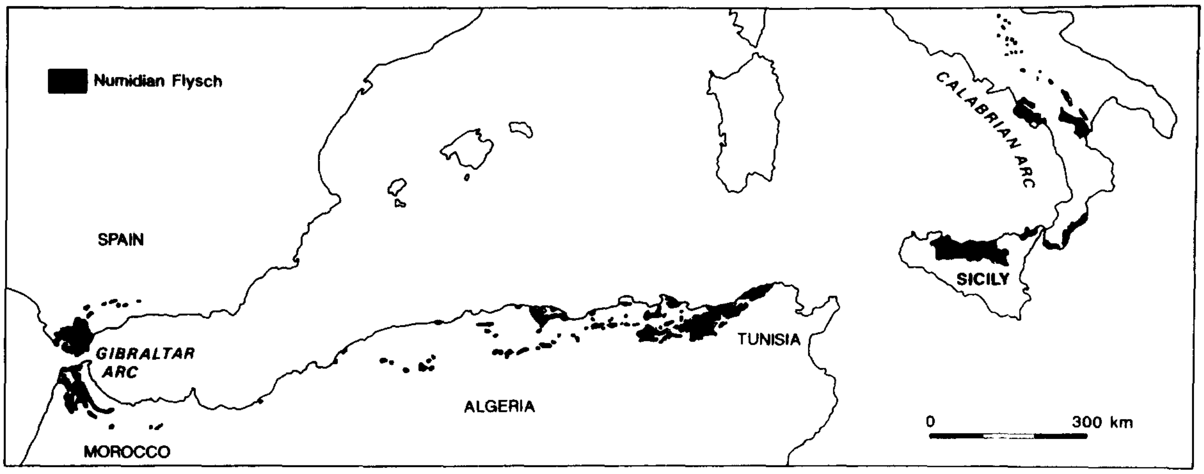


Fig. 1. Distribution of Oligocene–Miocene Numidian Flysch Formation in the western Mediterranean.

since the early papers of Broquet (1970) and Wezel (1970a,b).

The present work forms part of a more comprehensive study of deep-water massive sand deposits worldwide (Stow et al., 1996), and pulls together extensive field and laboratory data on three detailed case studies from northern Sicily. These include the sections exposed at Ponte Finale, Pollina and Contrada di Romano (Fig. 2). In addition, we have made detailed observations at other localities, including Cefalu, San Ambroggio, Castelbuono, Geraci, Mistretta and Sperlinga, which, although not reported here in detail, have provided a better understanding of the Sicilian Numidian Flysch as a whole (Fig. 3). Although the outcrops are good and the lateral geometry of some of the massive sandstone bodies can be measured, structural complications in the area should not be underestimated so that apparent geometries may be, in part, structurally controlled.

2. Geological setting

The geological history of Sicily has been the focus of considerable interest from the beginning of this century due to its relative position between the European and African plate margins. The kinematics of convergence has been extremely complex within the broad constraints imposed by the relative European–African plate movements. In order to place our own sedimentological work into a regional geological framework, we summarise below the Tertiary evolution of the western Mediterranean region, mainly following Dewey et al. (1989).

During the initial Numidian Flysch deposition in latest Eocene (Priabonian) times, the southeastern margin of the European plate (Corsica, Sardinia and Balearic islands) was separated from the north African rift margin by a 300 km wide Neotethyan slab of oceanic crust. The rifted African margin (encompassing the area of Sicily) consisted of a series of carbonate platforms and basins (D'Argenio et al., 1973; Scandone et al., 1974). Progressive closure of the main basin led to deformation of the carbonate platforms, the rifting of fragments from the European mainland and subsequent opening of new basins as the continental fragments underwent translation to the southeast.

From Late Oligocene to Early Miocene (Aquitanian) times, extensional tectonics were prevalent in the European area, with extension parallel to the Kybale–Calabria thrust belt (Fig. 4A). This led to associated compressional tectonics along the African margin. Subduction of the remaining oceanic crust led to the development of an accretionary wedge with a transport direction to the northeast (Knott, 1987), termed the Maghrebian accretionary prism (Fig. 4A). This period represents the main episode of sand supply to the various Numidian basins in the area (Selli, 1962; Oginiben, 1969; Giunta, 1985; Benomran et al., 1987) (Fig. 4B).

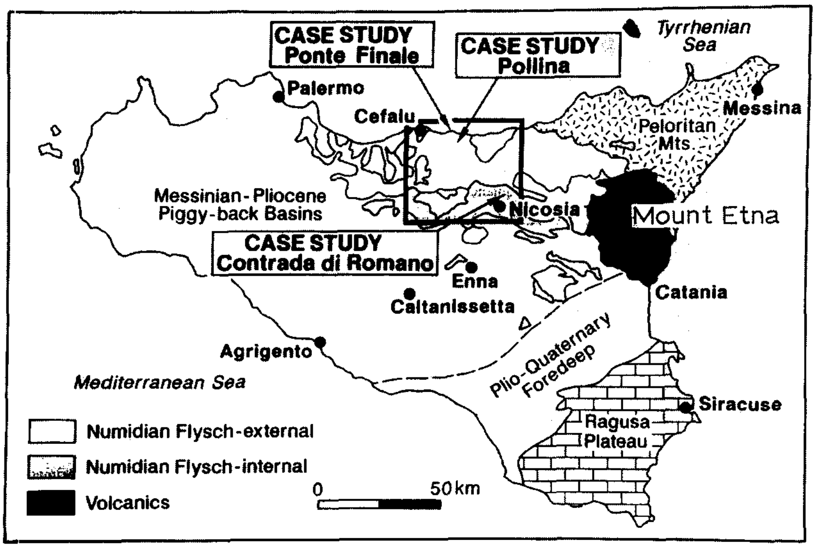


Fig. 2. Simplified geological map of Sicily showing the extent of the Numidian Flysch Formation and the three case study localities.

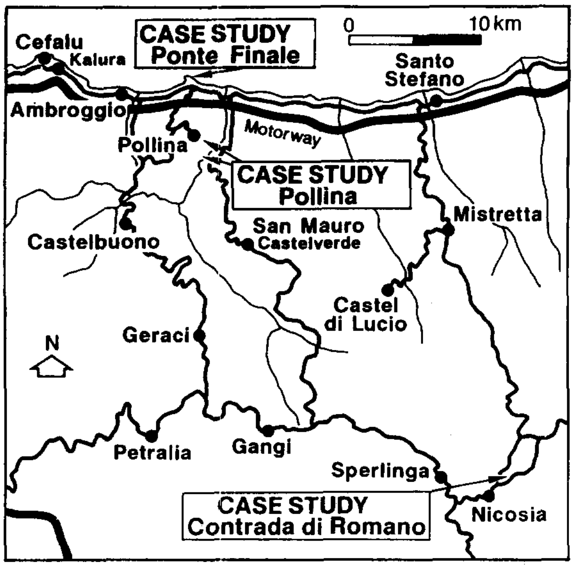


Fig. 3. Case study location map, northern Sicily. Ponte Finale, Pollina and Contrada di Romano locations highlighted.

The precursor to this sedimentation event is possibly related to the formation of a peripheral bulge on the North African margin causing the associated northward tilting of the shelf area toward the fronting foredeep allowing the Numidian Flysch sediments to overwelm the rapidly subsiding carbonate Panormide and Imerese platforms (Fig. 4B). The source of the Numidian is debateable but it seems most likely to have been shed northwards and eastwards from the African craton (Nubian Sandstones), in part via the 'Fortuna' delta.

Early Miocene–Burdigalian times saw the onset of widespread deformation in the region associated with the final consumption of oceanic crust and the subsequent rapid collision between the Liguride accretionary wedge and the Panormide platform. Along the North African margin this period saw the emplacement of the Kybale Range and associated deformation (Bouillin, 1984), limited calc-alkaline volcanism (Bellon, 1980) and the continuing deposition of Numidian Flysch into the linked basin system (Catalano and D'Argenio, 1978).

During Late Miocene–Tortonian times, the compressional regime extended throughout the Apennines, where thrusting was accompanied by the formation of a continuous foredeep in front of the chain. The continuation of the thrust belt advance saw the migration of the foredeep and piggy-back basins toward the Apulian platform (Pescatore, 1978). Numidian Flysch was cannibalised and resedimented from the piggy-back basins into the foredeep. Subsequently, the Numidian Flysch was carried on the varicoloured clay backthrust nappe over the Lagonegro basin, Panormide platform and the Liguride and Calabride complexes.

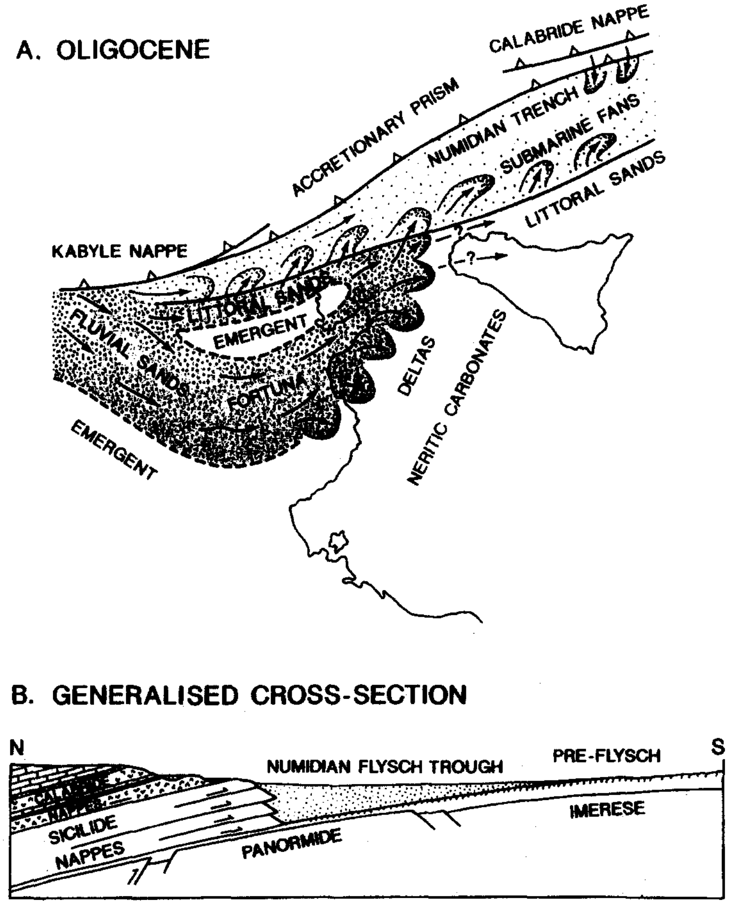


Fig. 4. (A) Palaeographic reconstruction of the central Mediterranean at the onset of the Numidian Flysch deposition. (B) Generalised N–S cross-section showing the squeezing and over-riding of the Numidian basin by nappe advance from the north (after Catalano and D'Argenio, 1978).

Consequently, the geology of Sicily is dominantly composed of subduction-related thrust slices which represent a post-Miocene accretionary prism assemblage (Roure et al., 1990). Three distinct tectonostratigraphic terranes can be identified in Sicily (Fig. 2):

- the European terrane, represented by the Peloritan mountains in the northeast;
- the African terrane covering much of the west and south of Sicily; and
- preserved fragments of the Neotethyan terrane sandwiched between the two.

The Numidian Flysch can be considered as partly deposited on Neotethyan oceanic crust and partly on African continental crust.

In Sicily the Numidian Flysch has been subdivided into three major units by Broquet (1968) and Duee (1969) (Figs. 2 and 6). These are:

- Numidian Internal — including many of the outcrops in the south, e.g. Contrada di Romano;
- Numidian External — including many of the more northerly and coastal outcrops, e.g. Ponte Finale and Pollina; and
- Numidian Intermediate — being a restricted belt between the Internal and External flysch, and having a rather more mixed composition.

The exact stratigraphic relationship between these units is not known, but both P. Broquet and G. Duee (pers. commun., 1991) interpret the Numidian Internal as a more distal equivalent of the Numidian

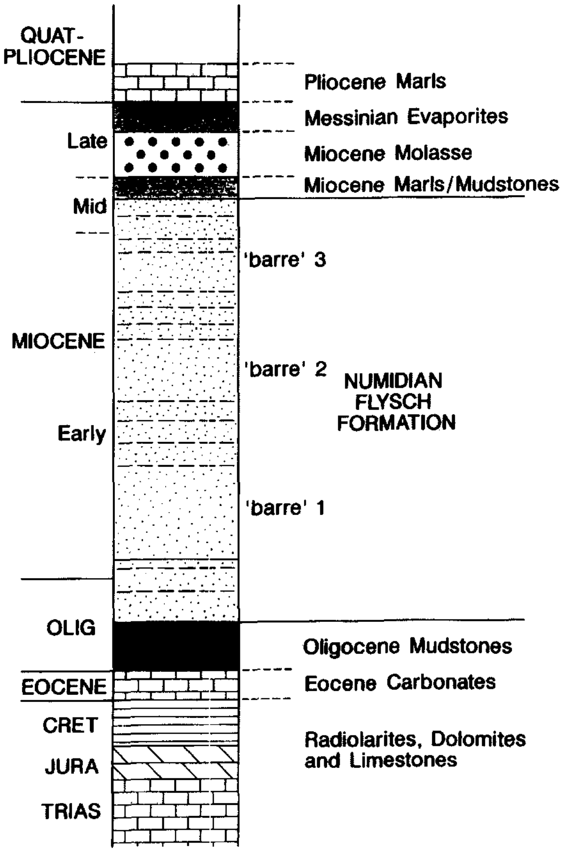


Fig. 5. Summary stratigraphic column for northern Sicily showing the age range of the Numidian Flysch Formation and the three main sandstone-rich intervals or 'barres'.

External, that has subsequently been thrust over and further southwards than the External flysch. These thrust units have an internally consistent stratigraphy, and allow the recognition of four main intervals (*barres*) of sandstone-dominated deposits separated by more mudstone/siltstone-rich intervals (Fig. 5). The total thickness of the Numidian Flysch varies considerably within Sicily up to a maximum in excess of 2 km (Fig. 6). Our study has focused on selected parts of this composite thickness in which the coarse-grained and more massive sandstone facies occur.

3. Sediment facies

Within the coarser-grained units of the Numidian Flysch, there are many examples of structureless, thick- and very thick-bedded sandstones, commonly referred to as massive sands. These and their associated facies (Fig. 7) can be considered as a massive sandstone facies association. The constituent facies of this association are described below for all three study areas taken together. We refer to bed thicknesses using standard descriptors as follows: thin (<0.1 m), medium (0.1–0.3 m), thick (0.3–1.0 m), and very thick (>1.0 m). Most of the very thick massive sandstone units (4–25 m or more) comprise amalgamated beds typically between 1 and 3 m in thickness.

3.1. Massive sandstone facies association

Structureless conglomerates and pebbly sandstones (Fig. 7c). True conglomerates with a dominant quartz-pebble composition tend to occur as thin to medium irregular beds, in some cases as a scour and lag deposit over an irregular surface. They are structureless, poorly sorted and with subrounded pebbles. These grade into pebbly sandstones in which the quartz-pebble content exceeds 10% and may reach 50% of the total. In both cases the pebbles are millimetric to centrimetric in size, rarely exceeding 3 cm in diameter.

Shale-clast conglomerates (Fig. 7a). These tend to occur as highly lenticular/erosive beds, typically from 10 cm to 1 m in thickness. They have a clast population characterised by abundant shale clasts, and are very poorly sorted with long-axis dimensions ranging from 1 cm to 50 cm (rarely more). The beds are either quite structureless or with crude coarse-tail grading, but shale-clast imbrication and long-axis alignment is apparent. The shale clasts are supported by a matrix of finer quartzose pebbles and coarse sand. In some cases they appear to form the lower part of a graded bed. This facies is most commonly identified at the Ponte Finale section.

Structureless sandstones/pebbly sandstones (Fig. 7a). These occur in thick to very thick beds. The beds are typically planar or slightly erosive, with sharp or amalgamated contacts. The facies are defined as having <10% pebble fraction, but there is a continuous gradation with the more pebble-rich sandstone facies (>10% pebbles). Sorting is poor to very poor. Water-escape structures are common in sediments of this facies, particularly in the Contrada di Romano section.

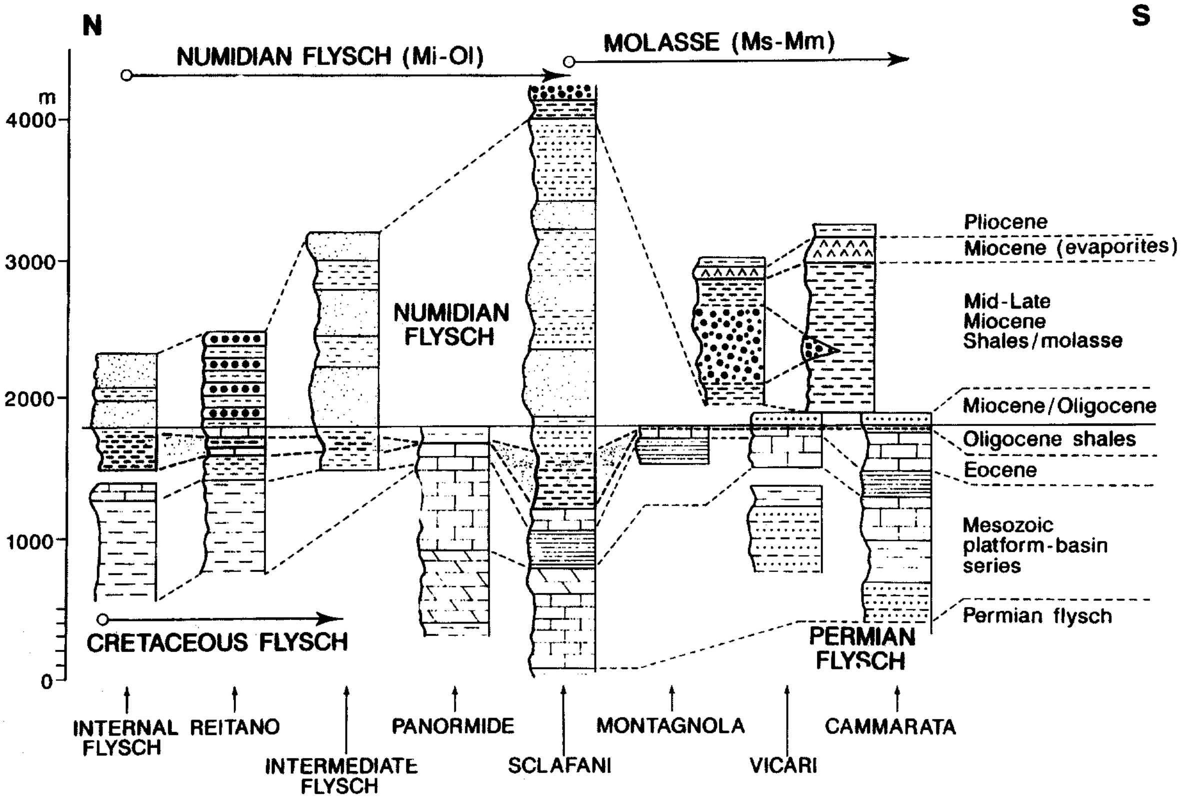


Fig. 6. Composite stratigraphic sections for northern Sicily showing the extent and variability of the Numidian Flysch Formation and associated lithostratigraphic units (after Broquet, 1970).

Graded sandstones/pebbly sandstones (Fig. 7e). These occur as thick to very thick beds throughout the succession. Grading is typically subtle, normal and may affect only the coarse tail fraction. Reverse graded bases are present in some of the thicker beds, but other structures are generally absent. The clasts are dominantly quartzose and shale, although other clast types are also observed. Sharp scoured bases and sharp tops are the norm. Composite graded beds with a shale-clast lower zone and quartz-pebble upper zone have been noted.

Stratified sandstones/pebbly sandstones (Fig. 7b). Both parallel-stratification and large-scale cross-stratification is observed, generally in thick to very thick beds. These beds may be amalgamated with other structureless facies to form thicker units.

Chaotic sedimentary units (Fig. 7d). Slump and slump/debrite units form a minor part of the massive sandstone facies association in some outcrops. They are more evident in the underlying fine-grained facies.

Sandstone–mudstone units. These are commonly interbedded with the other facies outlined above. They are thin- to thick-bedded and represent normal turbidites displaying the normal range of features and partial Bouma sequences of structures. The mudstone caps may be relatively thin and, where not present, the sediment has been assigned to the graded sandstone facies.

3.2. Associated facies

Those sediments occurring both below and adjacent to the channel complexes form a generally fine-grained interchannel facies association. Mudstones, silt-laminated mudstones and chaotic slumped mudstone units are the most abundant facies. These are interbedded with thin- and medium-bedded

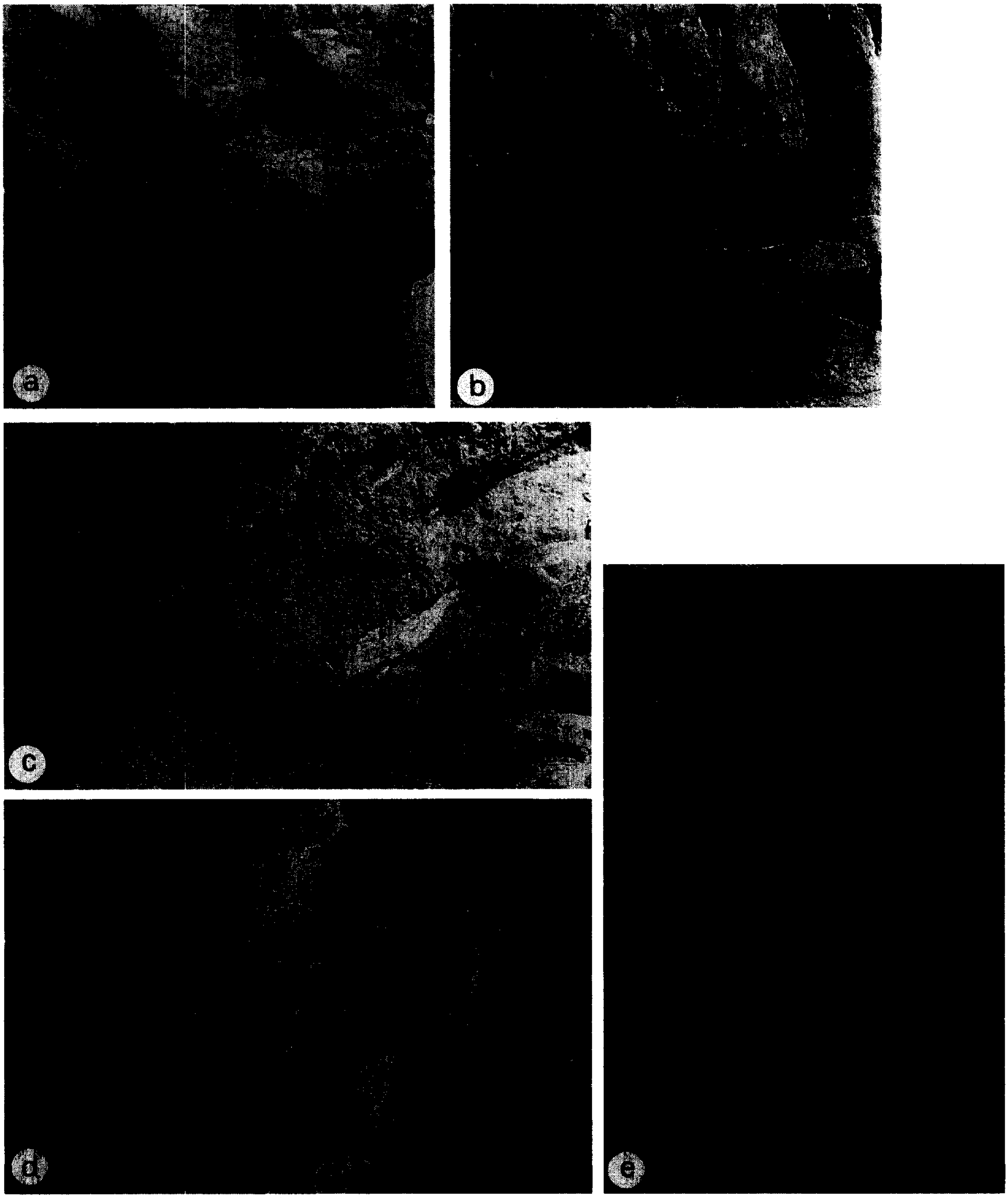


Fig. 7. Facies photographs, Ponte Finale. (a) Structureless sandstone over shale-clast conglomerate. (b) Stratified/cross-stratified sandstone. (c) Conglomerate, irregular lenticular body. (d) Muddy–sandy conglomerate, chaotic unit. (e) Graded pebbly sandstone, with grading of shale clasts.

sandstone–mudstone units that show the typical range of turbidite characteristics, including grading, Bouma sequences, sharp scoured bases, etc. Some of these beds are highly contorted, probably as a result of post-depositional liquefaction.

3.3. *Sandstone injection*

Thin sandstone dykes (5–15 cm thick) are observed in some cases to cut sharply through the finer-grained sediments surrounding the massive sandstone units. These may be fed from the base, margins or top of discrete sandstone bodies, and are seen to penetrate up to a few tens of metres into the adjacent sediment. Bedding-parallel injection of sands may be an explanation for some of the thin beds of structureless sandstone, although the evidence is equivocal.

4. Petrography

4.1. *Previous work*

It is partly because previous studies have found such a uniform and mature quartzarenitic composition for the Numidian sandstones, that the question of its ultimate provenance still remains open (e.g. Broquet, 1970; Wezel, 1970a; Gaudette et al., 1975; Hoyez, 1989). Most studies have found quartz percentages in excess of 90%, commonly >95%, with minor K-feldspar, mica and a zircon-tourmaline heavy mineral suite. Further work on the quartz has revealed a general dominance of monocrystalline ('common') quartz, but with between 30% and 60% polycrystalline quartz in the coarse size fraction (Wezel, 1970b). An original granitic source with some metamorphic input, followed by recycling through one or more episodes of sandstone deposition has been inferred.

4.2. *This study*

A range of samples from the Ponte Finale Numidian Flysch were examined and the resulting petrographic data show a close correspondence with earlier work, at least for the main coarse-grained facies. Recalculating our data to QFR (quartz–feldspar–rock fragments) percentages, by ignoring the 10–20% cement and 1–9% porosity values, yields quartz values of 85–95%, feldspar 2–8% and rock fragments 2–8%. Monocrystalline quartz is more common than polycrystalline, and K-feldspar more common than plagioclase. For these data, the quartz pebbles are assigned to the quartz percentage value, and the small number of other rock fragments are mostly of metamorphic origin.

A number of samples from the Pollina sections were also examined and a very similar and remarkably consistent petrography was found. QFR ratios show 90–97% quartz, with >90% of that being monocrystalline and only a minor feldspar–rock fragment component. Quartz overgrowth is the dominant cement and the porosity of most sections examined is low (<3%), although one example has secondary porosity up to 20%. At Contrada di Romano the sandstones have a very similar petrography. QFR ratios show 90–97% quartz, dominantly monocrystalline, and a very minor feldspar and rock fragment component. Quartz overgrowth is the dominant cement, although carbonate replacement cement is also noted. Porosities vary from low (<3%) to high (25%), the latter being a well-developed secondary porosity most probably due to intense surface weathering.

These results are fully compatible with an original Nubian Sandstone source from the African craton (Benomran et al., 1987).

5. Grain-size analysis

Textural studies indicate a great variation in grain-size characteristics for the Numidian Sandstones, with a bimodal pebble/medium sand being the most common grain-size distribution observed. In most cases, the sediments are well cemented and so detailed textural analysis is not possible. On the basis of thin-section study, however, the sandstones at Ponte Finale were found to have a medium to coarse mean grain size and, in many cases, a coarser, secondary granular or fine pebble mode. The sands tend to be poorly or very poorly sorted but individual grains, as well as quartz-pebble clasts, are typically subrounded to rounded. The subangular nature of some of the grains is thought to be a reflection of diagenetic change rather than depositional shape. In the Pollina sections, the sandstones are very similar to those examined at Ponte Finale. These sands are medium- to coarse-grained with a small fine pebble component, poor to moderately sorted with rounded to subrounded grains.

In contrast, the sandstones at Contrada di Romano are extremely friable and therefore detailed sieve analysis was possible. It was found that the sands are fine- to medium-grained (mean size) and relatively poorly sorted with both fine and coarse tails very evident on the grain-size distribution curves (Fig. 8a,b). Very little grain-size variation is evident in any of the closely spaced samples taken through a series of structureless sandstone beds and amalgamated units at the Contrada di Romano section.

A wider survey of textural properties from the three case study areas reported here (Ponte Finale, Pollina and Contrada di Romano) confirmed these characteristics and also showed a close correspondence between bed thickness and grain size. The thicker beds tend to have greater mean, maximum and matrix grain sizes and generally poorer sorting than the thinner beds. However, this does not apply to the true pebble conglomerates or shale-clast conglomerates at Ponte Finale or some of the very thick-bedded (i.e. >4 m) massive sandstones at Contrada di Romano, which have a relatively fine mean size and only moderately coarse maximum grain size (Fig. 8a,b).

6. Facies architecture

As a means of illustrating the characteristics and geometry of the various facies of the Numidian Flysch, three main case studies are used. For each case study the lateral extent of the beds and the vertical organisation of the facies are described, together with a summary of the principal facies types and their relative proportions. This work is depicted through logged sections, line drawings and selected plates. Two of the examples are located in the north, Ponte Finale and Pollina, and form part of the Numidian External; the third example is Contrada di Romano, which forms part of the Numidian Internal and is located to the south (Fig. 2).

6.1. Case Study 1: Ponte Finale

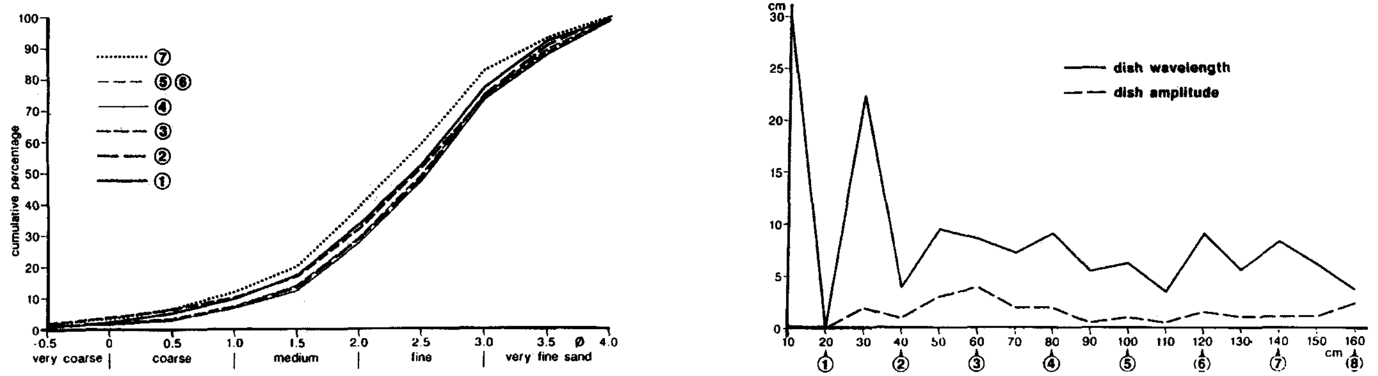
The outcrop at Ponte Finale is located along the coast some 9 km east of Cefalu (Fig. 3) and forms a prominent headland with steep sandstone cliffs, oriented approximately N–S. The best exposure extends for a distance of 1.2 km with stepped cliffs up to 80 m in height. Three channel-like sandstone complexes can be recognised (Fig. 9), ranging from 25 to 65 m in thickness and from 150 to 300 m in width. These values for channel sandstone thickness are minimum values as neither tops nor bases of the channels are fully preserved. Palaeocurrent measurements, principally from flute casts, groove marks and slump folds (Broquet, 1968; and this study), were determined at Ponte Finale and elsewhere along the coastal belt. These generally show west to east directed palaeocurrents.

6.1.1. Facies geometry

Channel 1 is between 25 and 55 m deep and 180–220 m wide, with a distinct stepped erosive southern channel margin and a steep northern margin. There appears to be an internal nested channel geometry. The channel fill comprises disorganised pebbly sandstones, stratified pebbly sandstones, very thick-bedded structureless sandstones and shale-clast conglomerates. Beds show a distinct lenticularity over a few tens of metres laterally as demonstrated clearly by the zones of shale-clast conglomerate in the southern segment of the channel complex (Fig. 10). Whereas the northern margin is faulted so that the original relationship with Channel 2 complex is uncertain, the southern margin is unaffected by tectonics and shows the original erosional contact downcutting into the underlying sediments.

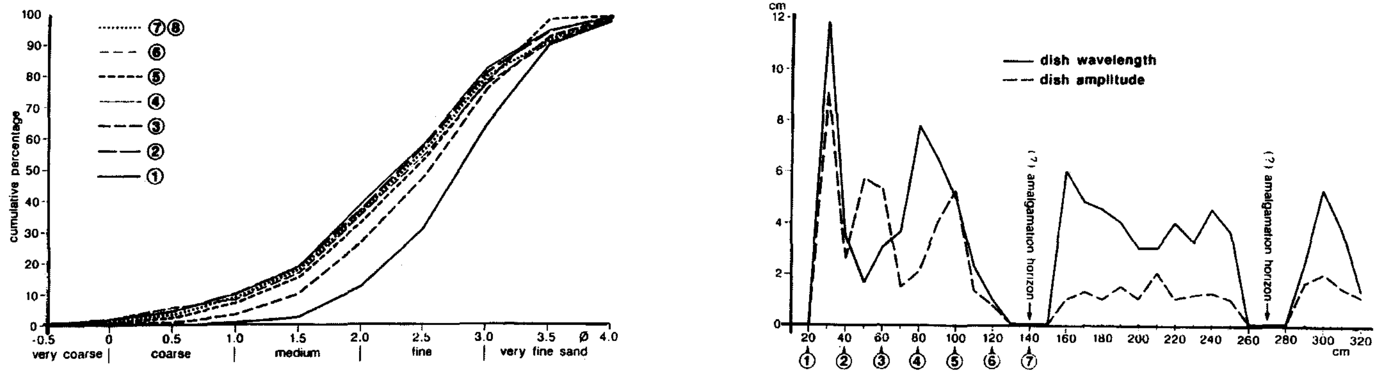
Channel 2 has faulted contacts on both margins thus giving a minimum lateral extent of 200–250 m, and depth of 35–55 m. However, these faults may reflect only minor adjustment of the original margins. The internal channel fill shows minor scouring (up to 5 m erosion), distinct stepped margins, and synsedimentary slump folds. The sediment fill package consists of thick-bedded structureless sandstones, structureless pebbly sands, shale-clast conglomerates and normally graded pebbly sandstones.

Channel 3 is at the point of the headland, so that only the southern margin is visible. This displays similar channel margin geometry to Channel 1 with marked erosive downcutting into the underlying sedimentary package. For the most part this margin appears to show the original contact between chan-



A. Cumulative frequency grain size plots for a series of samples (20cm spacing) through the lowermost bed shown in C.

C. Measurements of dish wavelength and amplitude for each 10cm interval through a 1.6m thick bed. Numbers indicate sample locations for grain size analyses.



B. Cumulative frequency grain size plots for a series of samples (20cm spacing) through the bed shown in A.

D. Measurements of dish wavelength and amplitude for each 10cm interval through a 3.2m thick (?)amalgamated sandstone unit. Numbers indicate sample locations for grain size analyses.

Fig. 8. Internal characteristics through thick- and very thick-bedded structureless sandstones with water-escape dish structures. (a) Cumulative frequency grain-size plots for a series of samples (20 cm spacing) through the lowermost bed shown in (c). (b) Cumulative frequency grain-size plots for a series of samples (20 cm spacing) through the lowermost bed shown in (a). (c) Measurements of dish wavelength and amplitude for each 10 cm interval through a 1.6 m thick bed. Numbers indicate sample locations of grain-size analyses. (d) Measurements of dish wavelength and amplitude for each 10 cm interval through a 3.2 m thick amalgamated sandstone unit. Numbers indicate sample locations of grain-size analyses.

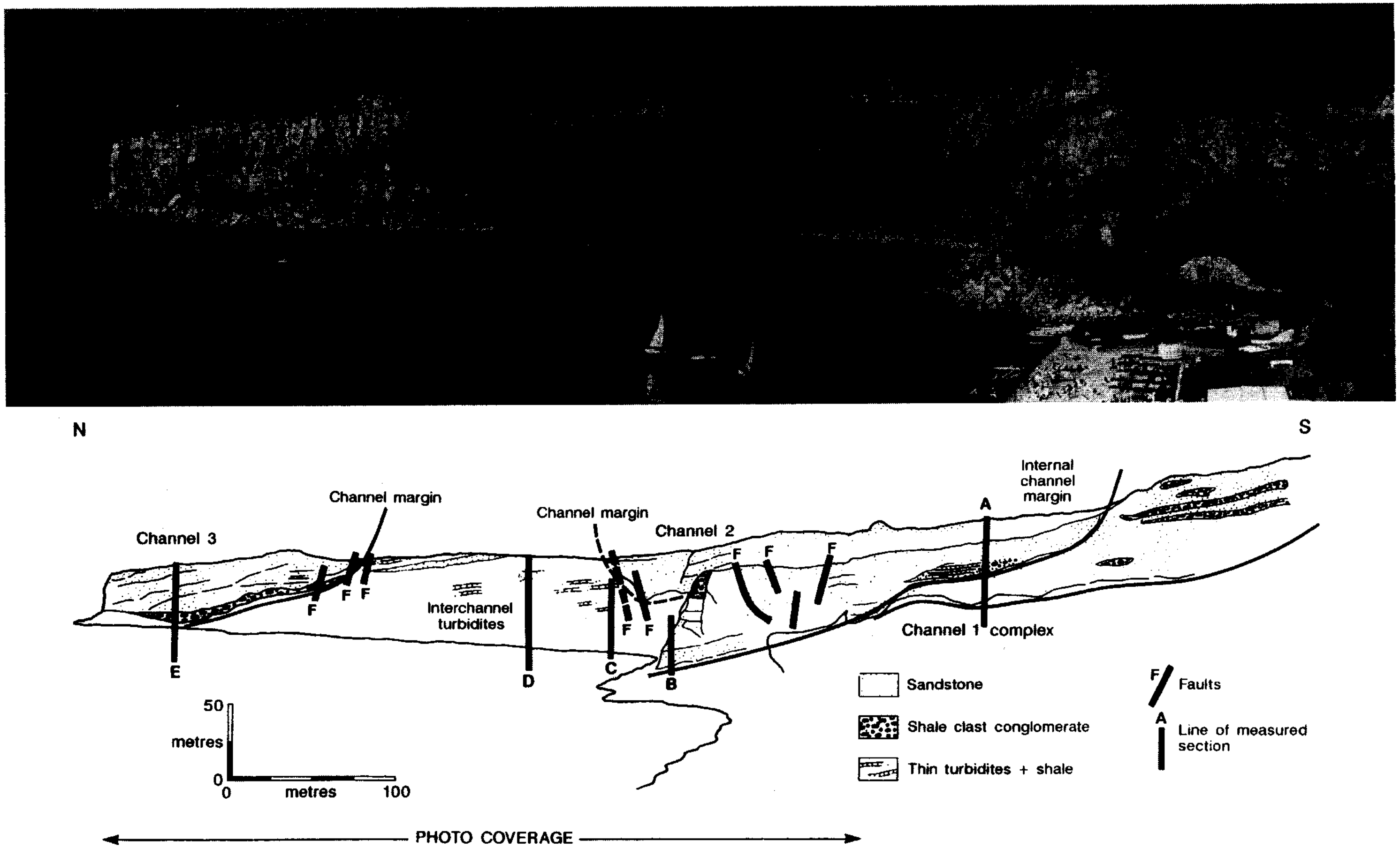


Fig. 9. Photograph (looking east) and line drawing interpretation of part of the Numidian Flysch (External) exposed at Ponte Finale. Parts of three channel complexes are inferred, although their present contacts with the interchannel turbidites are, in part, faulted.

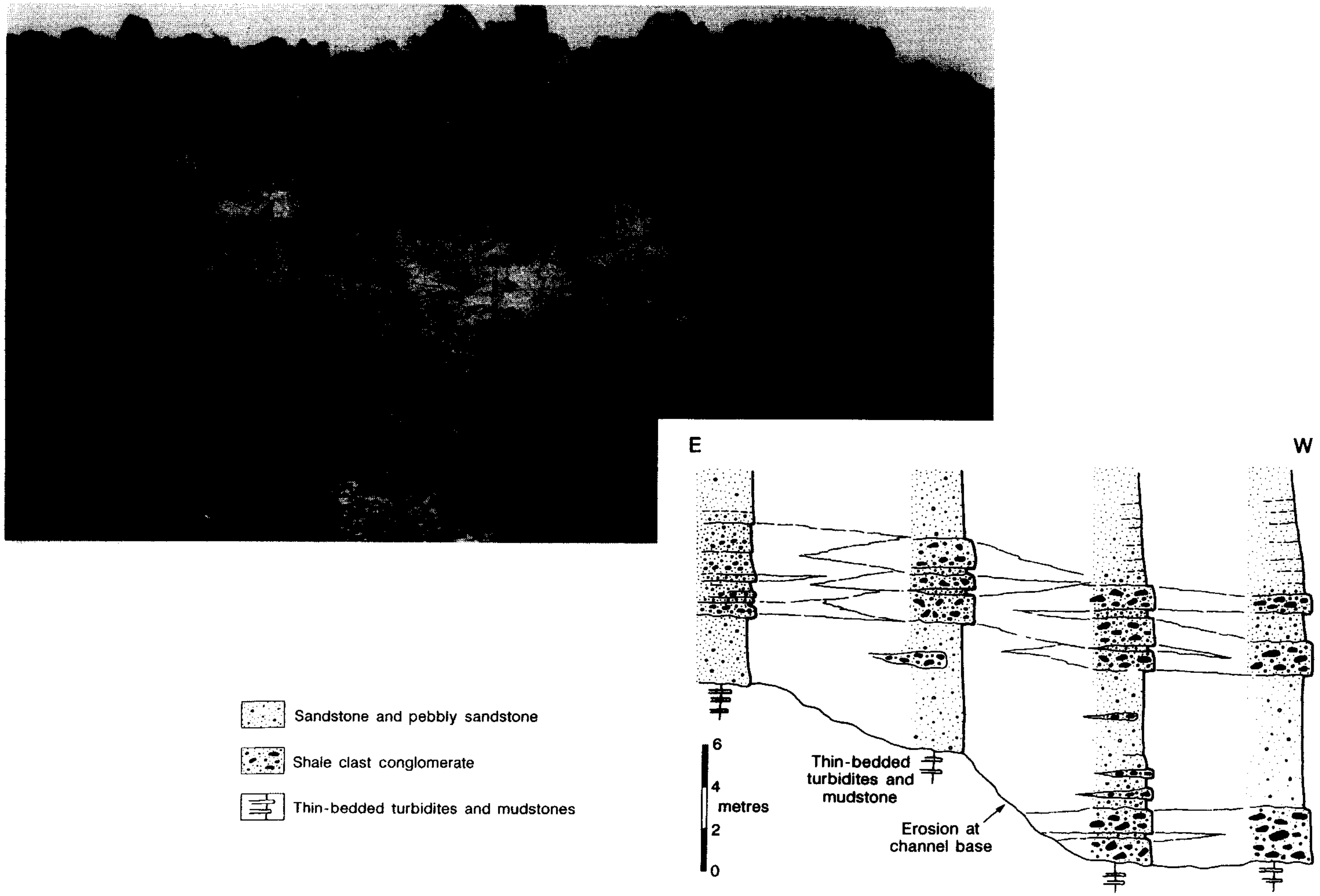


Fig. 10. Photograph and line drawing interpretation of erosion at base of Channel 1 (eastern end), Ponte Finale. Note lenticularity of shale-clast conglomerate zones and generally structureless aspect of sandstone/pebbly sandstone.

nel fill and interchannel deposits. Several small-scale (estimated throws 2–6 m) normal faults are present across the channel margin but, as currently active faults of this sort are well known from modern channels, we suggest that they are closely associated with the marginal zone of Channel 3 and were most likely synsedimentary in origin. The channel fill facies includes various conglomerate, shale-clast conglomerate, pebbly sandstone and massive sandstone facies similar to the other channels described.

6.1.2. Vertical succession

A series of five detailed logs were measured through parts of both the channel complexes and interchannel zones, and these are illustrated in Fig. 11. Precise locations of the logged sections are shown in Fig. 9. In general, there are no marked asymmetric trends of bed thickness or grain size (i.e. coarsening-upwards, fining-upwards, etc.) either within the channel or in non-channel sections. The channel complexes tend to be characterised by a 'blocky' sequence type with fairly random variations in bed thickness/grain size, whereas the fine-grained interchannel succession contains isolated packets or weakly asymmetric, small-scale sequences of coarser-grained turbidites.

6.1.3. Dominant sediment facies

The channel complexes are in part erosive into and in part laterally equivalent to a finer-grained mudstone association with thin- to medium-bedded sandstone turbidites. The sediment facies observed at Ponte Finale can be clearly divided into the massive sandstone facies association, which is 100% sandstone or coarser-grained, and the associated facies, which represent the relatively finer-grained interchannel sediments. These are shown in Table 1 and illustrated in Fig. 7.

Table 1
Numidian flysch sediment facies: Ponte Finale

Massive sandstone facies association	Approx. %
Structureless conglomerates and pebbly sandstones (pebble fraction > 10%, quartzose composition)	25–30
Shale-clast conglomerate	10–15
Structureless sandstone/pebbly sandstone (thick- to very thick-bedded, pebbles <10%)	25–30
Graded sandstone/pebbly sandstone (thick- to very thick-bedded)	20–25
Stratified sandstone/pebbly sandstone (thick- to very thick-bedded)	5–10
Chaotic sedimentary units (slump structures, debrite structures)	<3
Associated facies	
Sandstone–mudstone units, medium- to thin-bedded	
Silt-laminate mudstones	
Mudstones	
Chaotic sedimentary units (slumped, contorted)	

6.2. Case Study 2: Pollina

6.2.1. Pollina River

Along the course of Pollina River east of Pollina village, there is a laterally extensive outcrop over some 1.5 km of a steep valley side with a composite thickness in excess of 400 m (Figs. 12 and 13). The northeastern end of this outcrop shows stepped erosion of sandstones into an underlying mudstone-dominated succession, at least part of which is highly contorted and slumped. This northeastern part of the section comprises over 90% sandstones, pebbly sandstones and minor conglomerates occurring in thick to very thick beds and composite/amalgamated units (10–30 m thick), which have been numbered 1–10 in Figs. 12 and 13.

Tracing these units along section towards the southwest we can observe four distinct changes in character:

- individual units become progressively thinner and/or pinch-out completely;
- individual units divide into two or more distinct sandstone beds separated by mudstones;
- the sandstone/mudstone ratio decreases; and
- there is an apparent upsection migration of the sand-rich lithologies, although the present topography prevents unequivocal confirmation of this trend.

The upper units that only appear in the central and western part of the outcrop are numbered 11–15.

6.2.2. Pollina village

The village of Pollina is built on the top of a prominent sandstone-capped knoll (Fig. 14). This sandstone/conglomerate-dominated assemblage has a maximum thickness of about 150 m overlying a mudstone-rich association with large-scale slump struc-

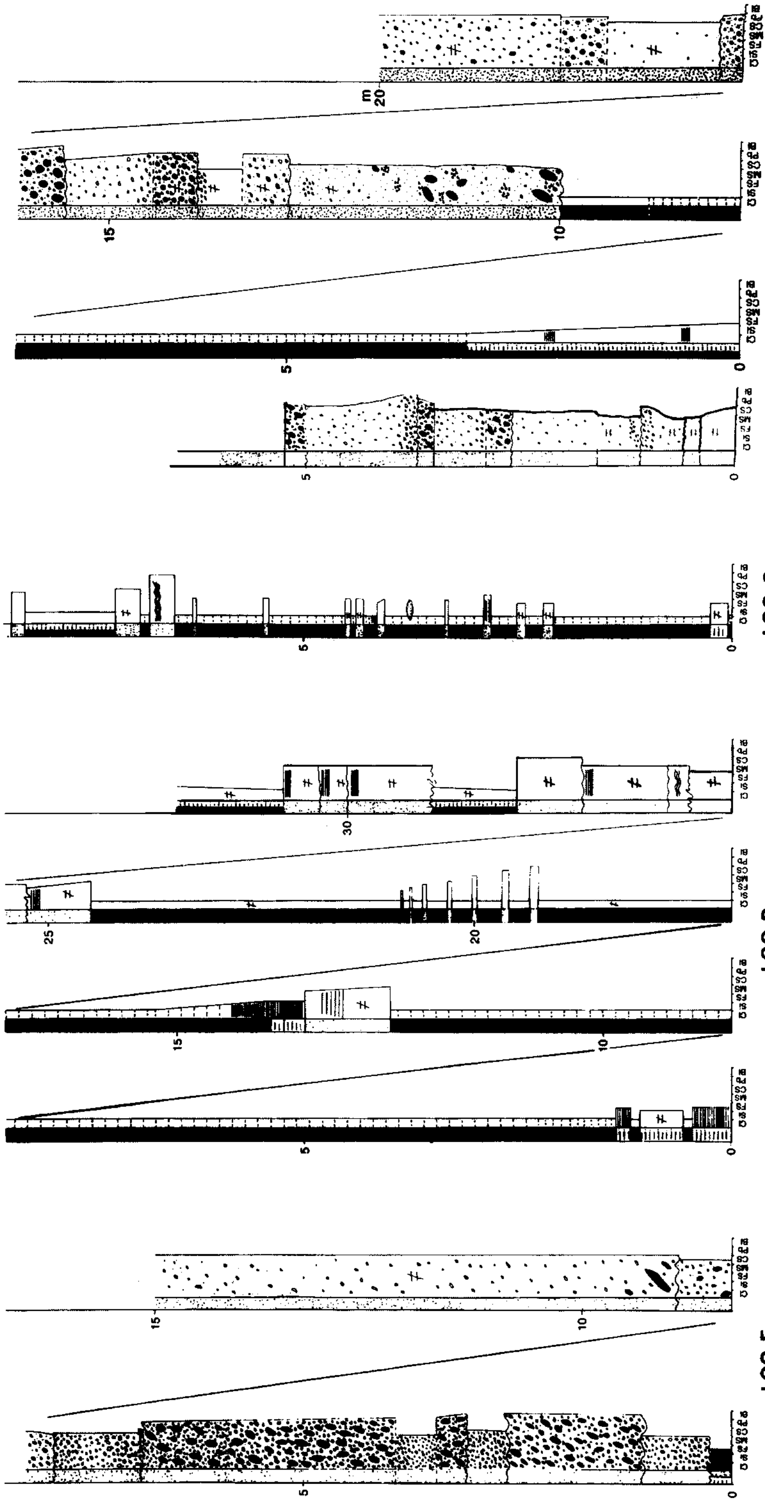


Fig. 11. Detailed graphic logs through parts of the Ponte Finale channel/interchannel complex (See Fig. 9 for location).

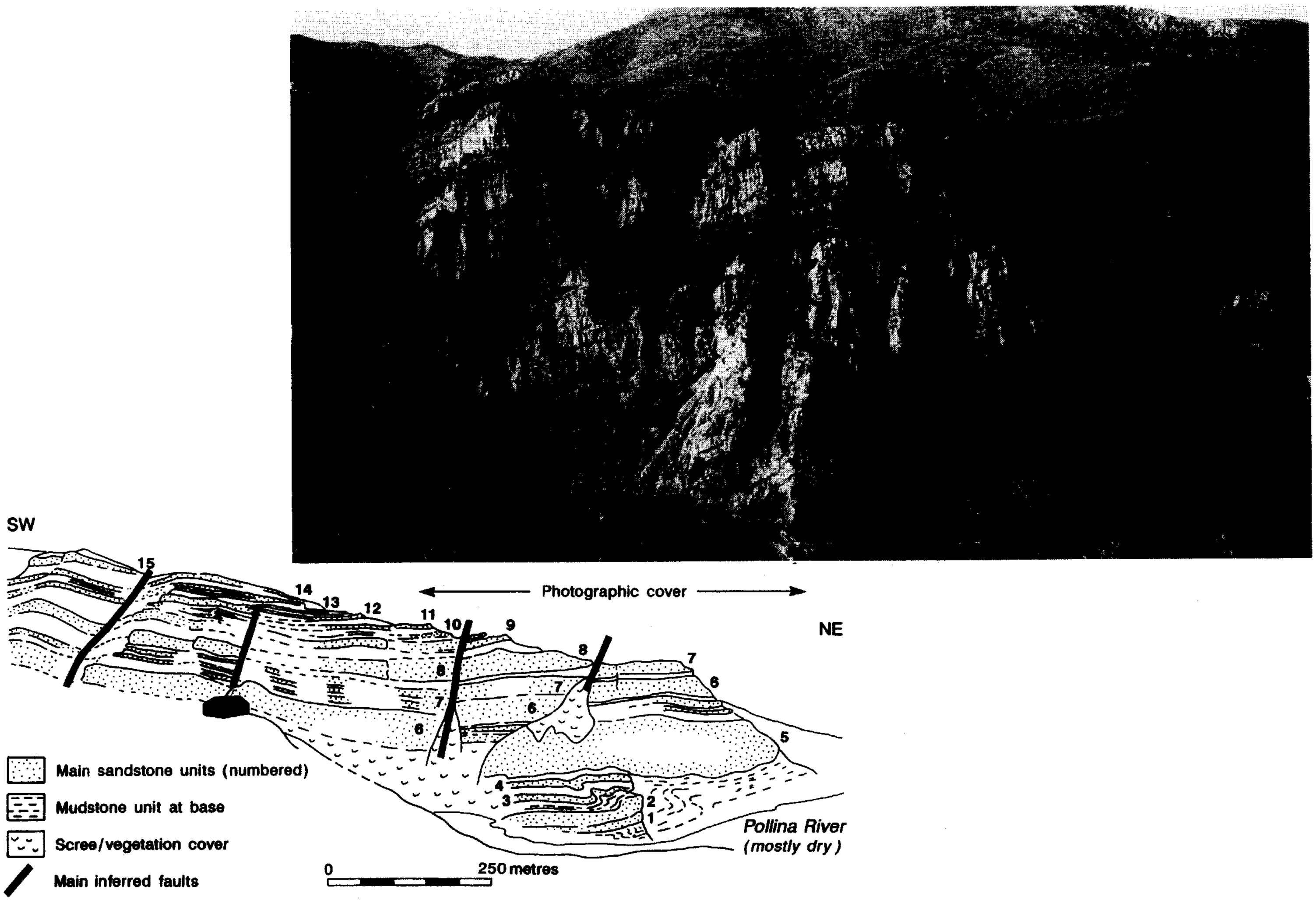


Fig. 12. Photograph and line drawing interpretation of the Pollina River section. Major sandstone units numbered 1–15. Relatively little displacement apparent across inferred fault zones.

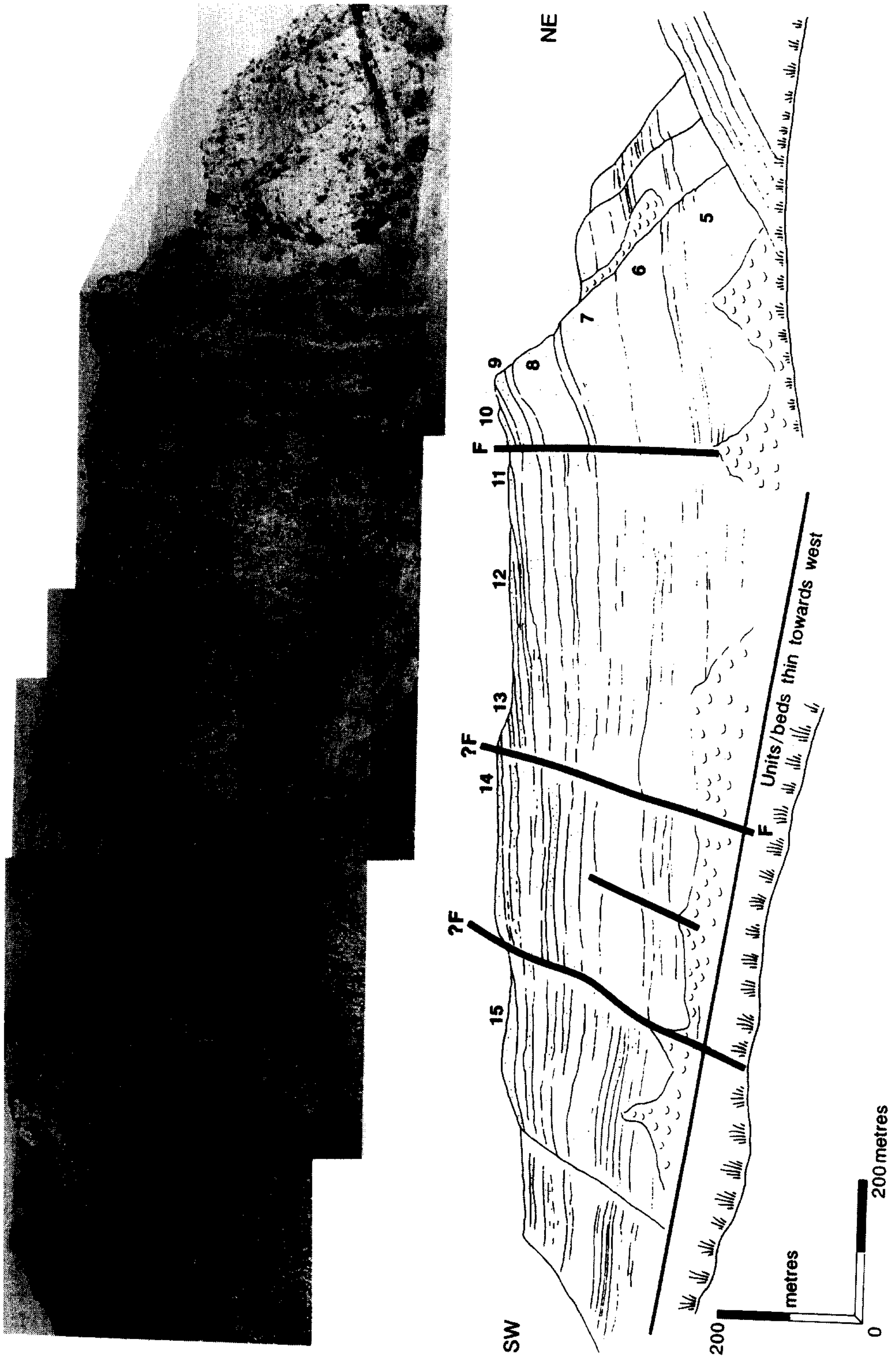


Fig. 13. Photographic montage and line drawing interpretation of the Pollina River section. Major sandstone units numbered 5–15 (as in Fig. 12). Channel migration inferred towards the southwest.

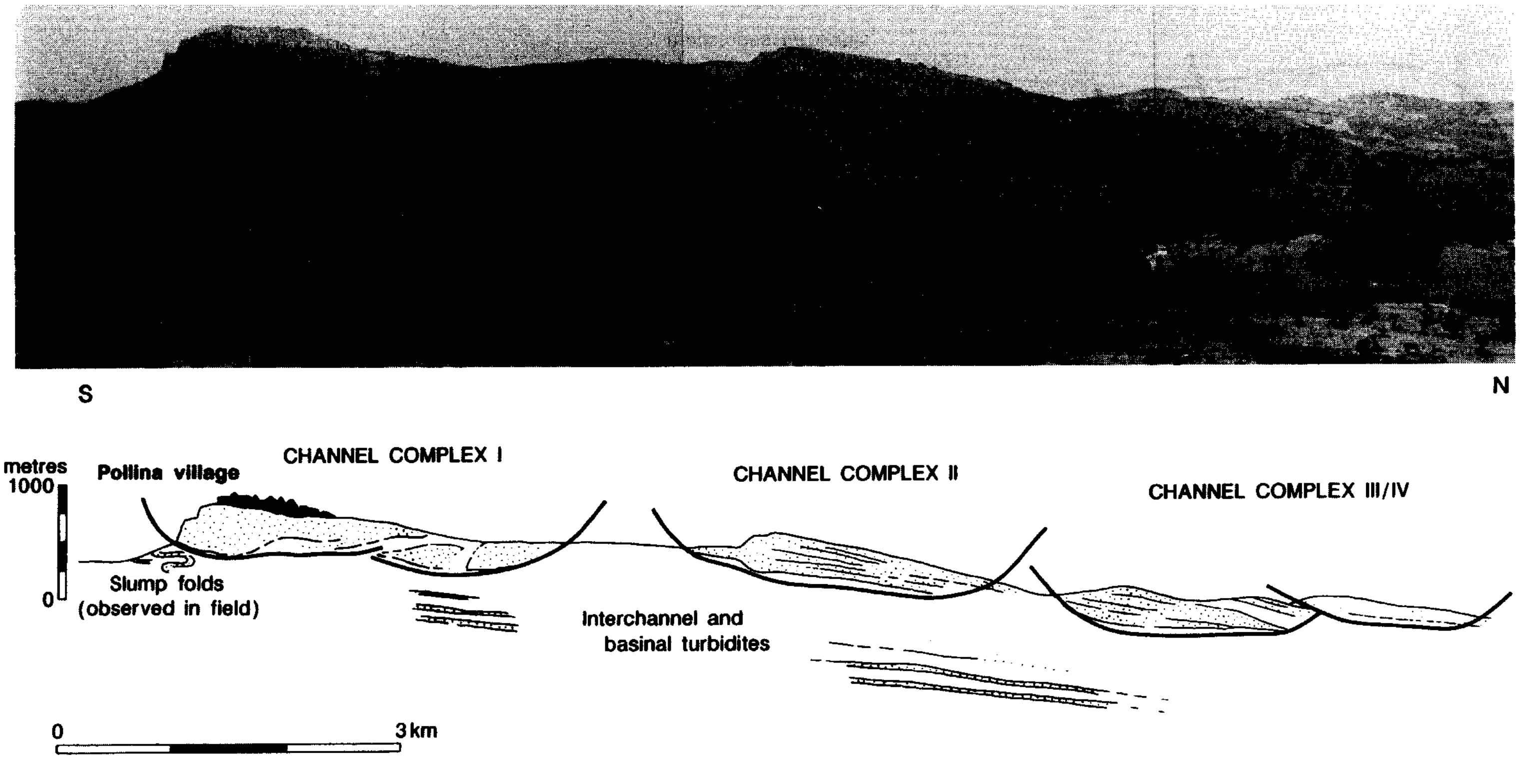


Fig. 14. Photographic montage and line drawing interpretation of Pollina village section and associated massive sandstone channel complexes on the Pollina Ridge.

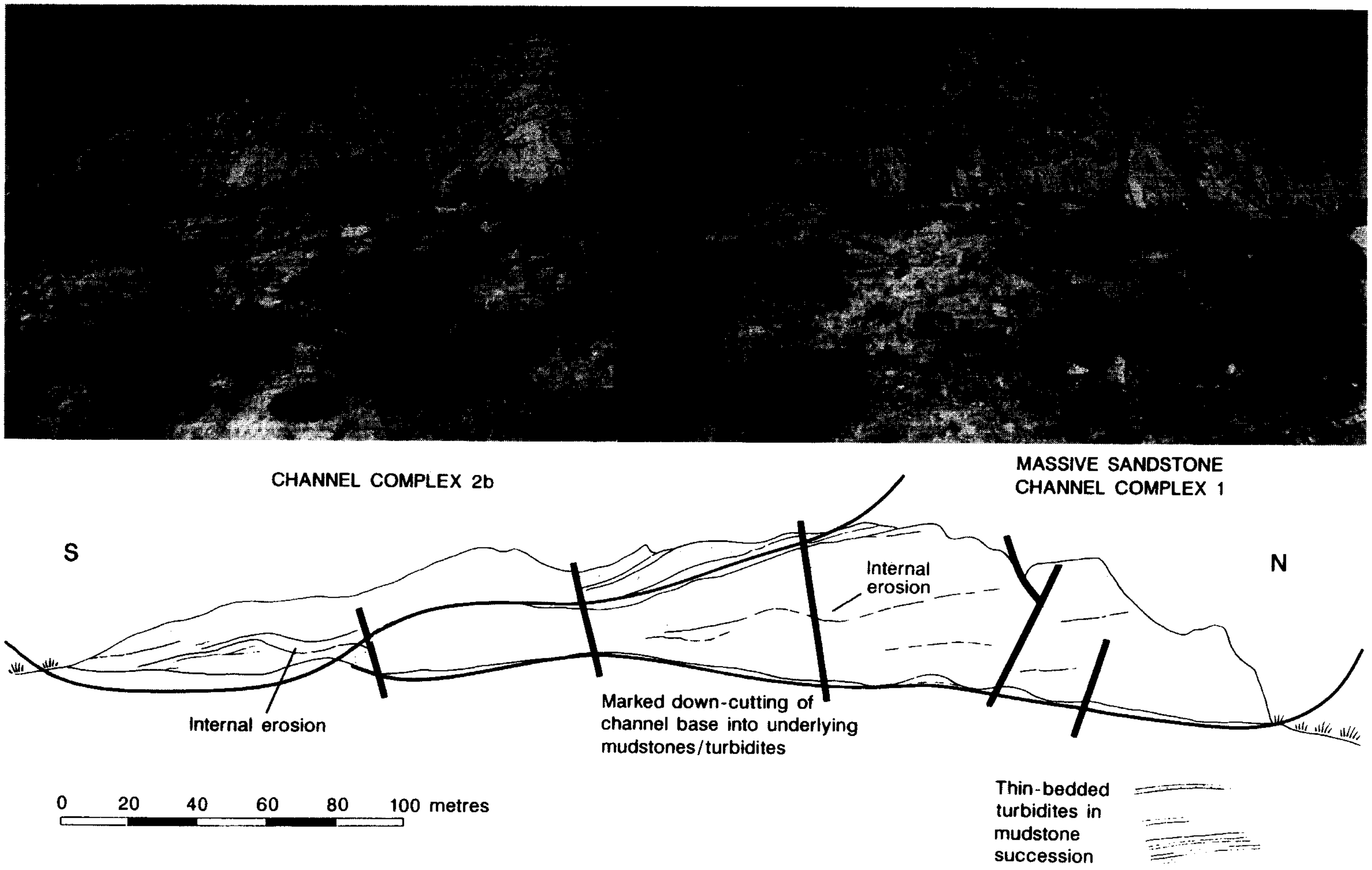


Fig. 15. Photographic montage and line drawing interpretation of Ambroggio bridge section.

tures. Viewed from a distance, either from west or east of the village, this sandstone complex is seen to thin markedly and pinch-out completely over a distance of some 2–3 km to the north, down a narrow ridge that inclines gently towards the coast near Ponte Finale. The southern part of this lenticular body is cut abruptly by the steep topographic slope on which the village sits. Three similar lenticular sandstone bodies occur at intervals down the Pollina Ridge towards the coast, either in the same stratigraphic location as Pollina village or slightly deeper within the section. All appear to be encased in a finer-grained mudstone lithology and range from about 1 km to 3 km in extent, and 75 m to 300 m in thickness.

Due to general inaccessibility of the terrane as well as a thick and prickly scrub vegetation cover, these sandstone lenses were not traced out over the ground. In general, however, they appear to show the same sort of unit thinning and subdivision away from the thickest part of the lens as documented in more detail for the Pollina River section. Parts of these successions appear to comprise very thick (tens of metres) massive sandstone units.

6.2.3. Ambroggio bridge

West of Pollina Ridge and closer to the coast near Ambroggio, a lenticular sandstone complex bearing close similarity to the smaller lenses observed along the Ridge, is exposed in the hillside flanking a small dry stream (Fig. 15). During the course of this study, the hillside was being actively tunnelled to allow passage of the coastal *Autostrada*.

Although several normal faults now cut through the sandstones, there appears to be relatively little displacement along them so that original relationships can be inferred. Overall, the lenticular body is some 300–400 m wide and 60–80 m thick and extends along the coast (beneath the Ambroggio hillside) for some 500 m. In this E–W direction the outcrop is truncated by the local topography.

The sandstone bodies appear to form a nested channel complex eroded into a mudstone-rich encasing lithology that includes numerous thin to thick turbidite sandstone beds. Internally the main bodies comprise very thick, structureless and amalgamated units of sandstone and pebbly sandstone, with limited grading and few other structures evident. There is much evidence of internal erosion of one sandstone unit into another and marked lateral thinning of units and beds. Upwards, the channel fill complex becomes thinner-bedded and with a lower sandstone/mudstone ratio. Individual sandstone bodies become partly separated from other sandstones by interbedded finer-grained lithologies.

6.2.4. Other sections

A number of other sections of sandstone- and conglomerate-dominated successions were observed in the region between the coastal outcrops of Ponte Finale–Kalura and those of the Numidian Internal at Nicosia (Contrada di Romano). Most of these are interpreted as part of the Numidian External (P. Broquet and G. Duee, pers. commun., 1991), although the isolated position of some and the possibility of hidden faults makes this stratigraphic inference uncertain in some cases.

Those that were examined show many of the features outlined above. Lenticular bodies of 1–3 km width and 50–200 m thickness were noted both to the north and south of Castelbuono, at Geraci and along the hillside above Vallon di Mora. Details of channel-like erosion at the base of thick massive sandstone bodies were noted at Mistretta and on the hillside east of Pollina. This erosion was typically associated with slumped mudstones, slump structures within the sandstones, trains of shale clasts (up to 1 m and more in size) and, more rarely, with sandstone dykes injected into the encasing mudstones.

6.2.5. Vertical succession

The relative thickness of the Pollina sections compared with those at Ponte Finale and Contrada di Romano, together with the range of localities examined within the Pollina area, allow us to make some generalisations about macro-, meso- and microsequences in the Numidian Flysch External.

The macro- or basin-fill sequence is most difficult to ascertain because of the tectonic disruption caused by nappe emplacement. Nevertheless, careful studies by Broquet (1968), Duee (1969) and Wezel (1970a) have identified four separate and broadly correlative intervals (or 'barres') of conglomerates and sandstones within the mudstone-dominated basin succession where it is thickest (approx. 2 km). This pulsed cyclicity is most likely due to allocyclic controls such as tectonic activity or sea-level change.

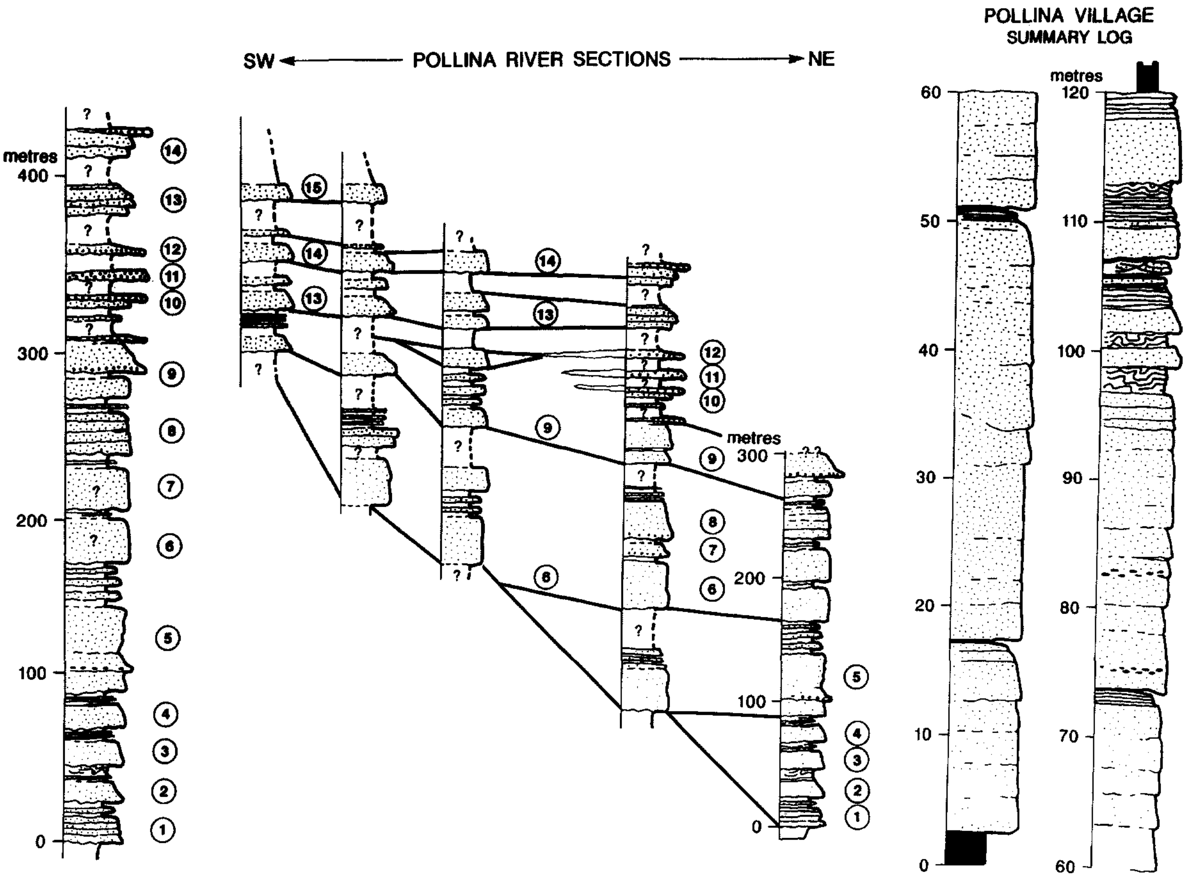


Fig. 16. Summary graphic logs of Pollina River and Pollina village sections. The numbers refer to the main sandstone units indicated on sketch section (Figs. 12 and 13).

Where we have examined parts of these 'barres' in detail (Fig. 16), they commonly show much evidence of lateral variation and discontinuity caused, most probably, by channelling. A typical channel mesosequence comprises a coarse-grained sandstone-dominated package (50–250 m thick) abruptly overlying and erosive into a mudstone sequence with thin-bedded sandstone/siltstone turbidites. Extensive slumping characterises the upper part of the mudstones, whereas the lower part of the channel association may include slumped units, conglomerate scour–lag deposits, single large isolated shale clasts and shale-clast conglomerates in discontinuous/lenticular beds. The rest of the channel fill comprises the normal range of coarse-grained sediments found in the massive sandstone facies association.

There is no standard facies arrangement within the body of every channel fill succession. In some cases, particularly the smaller channels (i.e. around 50 m thick), there is a blocky mesosequence with both abrupt appearance and disappearance of the coarse-grained facies. In other cases, there is clear evidence of a second and maybe third channel eroding into the earlier ones to form a nested channel mesosequence with conglomerate scour–lag and shale-clast conglomerate facies near the base of each successive channel. For the larger channels (i.e. in excess of 200 m thick), there may be significant lateral channel migration upsection, as well as a generally fining-upwards mesosequence, at least over the upper few tens of metres of channel fill.

At the small scale (say 5–20 m), very little system was observed in terms of microsequences of facies. Repeated amalgamation and suspected amalgamation of beds, together with obvious internal erosion surfaces, mitigate against the recognition of such sequences if they existed. The thickness variations noted (Fig. 17) may in some cases be caused by slight topographic compensation by successive high-density turbidity currents. This effect is perhaps more evident where thickness variations of successive sandstone units can be traced laterally over hundreds of metres (Figs. 12 and 13).

6.2.6. Dominant sediment facies

The sediment facies observed in the Pollina River and village sections, together with those throughout the broader area of Numidian Flysch External considered in this case study (Fig. 3), are very similar to those already described from Ponte Finale. There are a few additions and a much broader range of relative abundances of the different facies (Table 2). Some sections are characterised by more normal, thin- to thick-bedded turbidites, rather than massive sandstones and cannot therefore be included within the massive sandstone facies association. In general, there are fewer of the coarser-grained facies, the conglomerates and shale-clast conglomerates, than along the coastal sections.

Table 2
Numidian flysch sediment facies: Pollina (and region)

Massive sandstone facies association	Approx. % (range)
Structureless conglomerates and pebbly sandstones (pebble fraction > 10%, quartzose composition)	0–10
Shale-clast conglomerate	0– 5
Structureless sandstone/pebbly sandstone (thick- to very thick-bedded, pebbles <10%)	30–50
Graded sandstone/pebbly sandstone (thick- to very thick-bedded, including megaturbidites)	25–45
Stratified sandstone/pebbly sandstone (thick- to very thick-bedded)	5–10
Chaotic sedimentary units (slump structures, debrite structures)	1– 5
Sandstone–mudstone units (thin- to thick-bedded)	5–25
Mudstones (± silt lamination)	0–15
Associated facies	
Muddy sandstones, thin- to medium-bedded	
Sandstone–mudstone units, thin- to thick-bedded	
Silt-laminated mudstones	
Mudstones (varicoloured, ± bioturbation)	
Chaotic sedimentary units (slumped, contorted)	
Cherts and siliceous micrites	
Carbonate turbidites	
Ferromanganese/burrowed horizon	
Sandstone dykes	

We summarise briefly below some of the more important aspects of the Pollina region facies, particularly where these differ from those described at Ponte Finale. These features are illustrated in Fig. 18. The structureless conglomerates/pebbly sandstones are relatively rare (0–10%). They are structureless, poorly sorted and with subrounded pebbles of millimetric to centimetric size. They tend to occur as thin lag horizons or as the lower parts of thicker graded beds. The shale-clast conglomerates are also much less common (0–5%) in the Pollina sections than along the coast. Much more common are large isolated shale clasts, up to decimetric and even metric size, which occur 'floating' in the massive sandstone facies, or much smaller clasts that form dispersed pebbles in the pebbly sandstone facies.

The structureless sandstones and pebbly sandstones, in which the pebble fraction is generally small in size and never exceeds 10% of the whole, is one of the two most abundant facies present (30–50%). They can be thick- to very thick-bedded, typically amalgamated into still thicker sandstone units. The sorting is poor to very poor and water-escape structures are rare. The graded sandstones/pebbly sandstones (pebbles <10%) are the other most abundant facies present (25–45%). Beds are medium to very thick and display both normal and reverse distribution and coarse-tail grading. Grading is often quite subtle and, in some cases, indicates a megaturbidite (i.e. >10 m thick graded bed). In other cases the grading indicates the A-division of a normal coarse-grained turbidite. Stratified sandstones/pebbly sandstones (pebbles <10%) occur less commonly as an isolated facies (5–10%), but both parallel- and cross-lamination are observed as parts of more normal turbidite beds.

Chaotic sedimentary units formed by slumping or debris flow processes are a minor facies (1–5%) but consistently present in most sections examined. They are still more characteristic of the subjacent fine-grained facies association. The sandstone–mudstone units are commonly (5–25%) interbed-

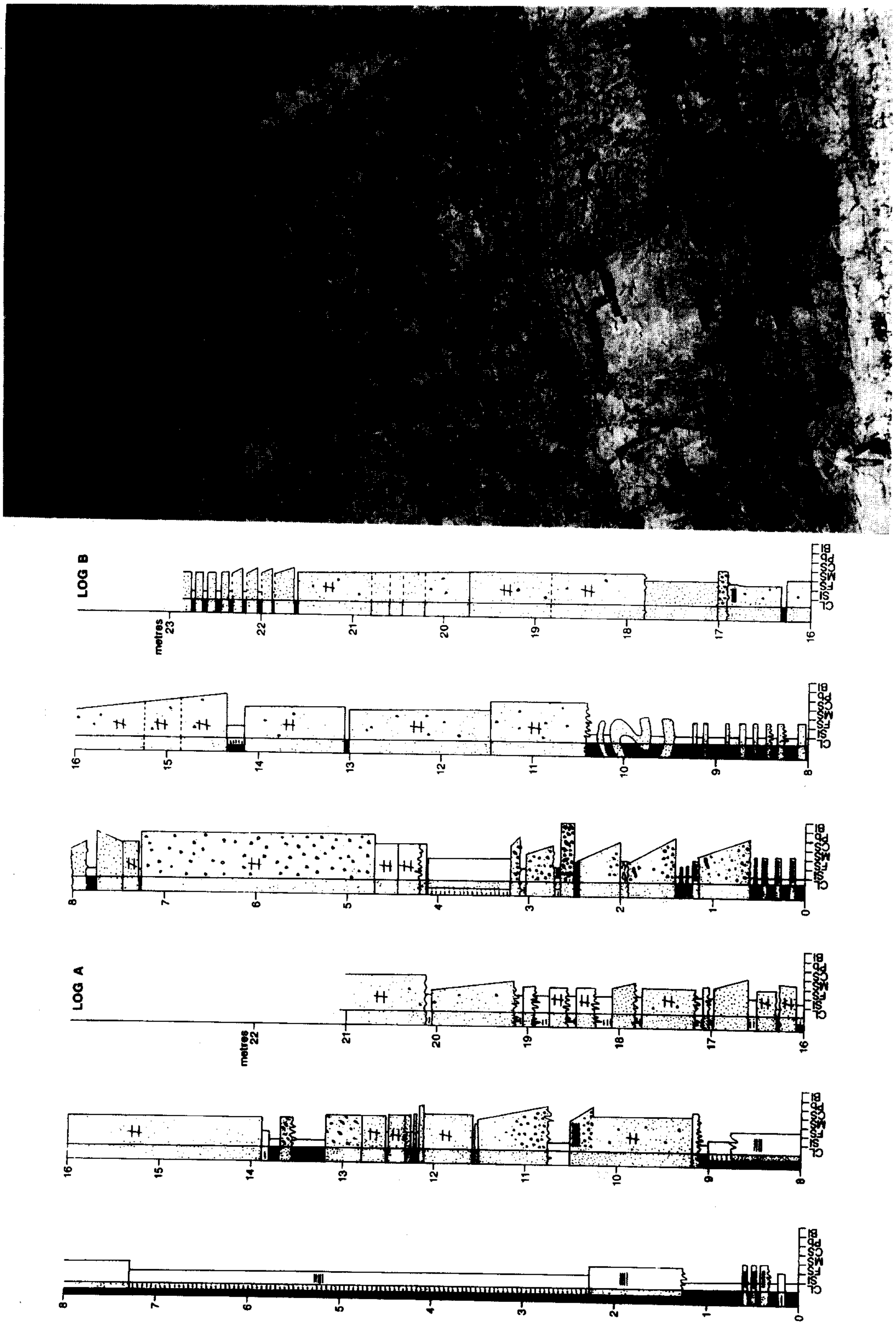


Fig. 17. Detailed graphic logs of parts of the northeastern end of Pollina River section. The photograph shows the lower 18 m of section. Figure for scale.

ded with the other facies outlined above. They are thin- to thick-bedded and represent normal turbidites displaying the normal range of features and partial Bouma sequences of structures. The mudstone caps may be relatively thin and, where not present, the sediment has been assigned to the graded sandstone facies.

A broad range of associated facies have been recognised in the sediments surrounding the massive sandstone facies complexes. Typically, these are mudstones and silt-laminated mudstones with a variable proportion of interbedded graded sandstone–mudstone turbidites. For the most part the mudstones are not well preserved and weathered badly at outcrop so that it is difficult to ascertain their exact nature and origin. Where siltstone laminae are present then fine-grained turbidite characteristics are often evident. In other cases, the mudstones are varicoloured, mottled and may have distinct bioturbation traces, more characteristic of hemipelagites and/or contourites. Cherts and siliceous micrites are locally present and one extensive horizon beneath the Numidian Flysch sensu stricto is characterised by ferromanganese encrustation and burrows.

Chaotic or slumped units are relatively common, especially immediately adjacent to the massive sandstones, as are sandstone dykes and other features indicative of secondary remobilisation and injection.

6.3. Case Study 3: Contrada di Romano

In the vicinity of Nicosia and Sperlinga (Fig. 3) there are a series of isolated highs and prominent sandstone bluffs that represent the coarse-grained association of the Numidian Flysch Internal. The towns of Nicosia and Sperlinga are themselves built on and around such bluffs as is the village at Contrada di Romano, some 2 km northeast of Nicosia.

East and southeast from Nicosia the sandstone bodies are distinctly isolated and encased in a widespread fine-grained facies association. Folds, overturned folds and thrust slices are in evidence so that it is unclear to what extent the sandstones have become isolated by tectonic emplacement. However, their overall geometries are not dissimilar from those observed in the Numidian External (Ponte Finale and Pollina) where the nappe displacement has apparently been less and the stratigraphic relationships have remained more clearly intact. In addition, the sandstone complex at Sperlinga is part of a broad synclinorium in which the sandstone can be correlated over some 18 km, so that there appears to be at least some integrity to the Numidian Flysch in this region.

6.3.1. Facies geometry

The sandstone bluff at Contrada di Romano is some 40–45 m thick and 450–500 m long (Fig. 19). Detailed examination of the sedimentary features indicate that it is stratigraphically inverted and so probably represents the overturned limb of a nappe fold. For the most part, it is made up of very thick uniform structureless sandstone units that appear to be incised into medium- and thick-bedded sandstones.

There is also some evidence for lateral thickening of beds into full amalgamated units from south towards the north. The sandstones are overlain (stratigraphically) by mudstones, siltstones and thin sandstone turbidites, and it is assumed that these facies are probably also the lateral equivalent of the massive sandstone complex. Isolated blocks and stringers of massive sandstone can be observed in the poorly exposed, vegetation-covered terrane. These sandstones may have been formed by injection into the (stratigraphically) overlying mudstone unit.

6.3.2. Vertical succession

The Contrada di Romano succession studied in detail represents an isolated massive sandstone complex within a mudstone facies association, although we cannot be entirely certain of the stratigraphically underlying unit, which has now been eroded away. As a whole it can be characterised as a blocky mesosequence with a preserved sharp erosive base and an equally abrupt top. The measured sections (Fig. 20) reflect the general homogeneity of this mesosequence.

6.3.3. Dominant sediment facies

The sediment facies observed in the Contrada di Romano section are somewhat dissimilar to those already described for the Numidian Flysch External case studies (Ponte Finale and Pollina), being generally more restricted in type and finer in grain size (Table 3, Fig. 21). There is a clear distinction

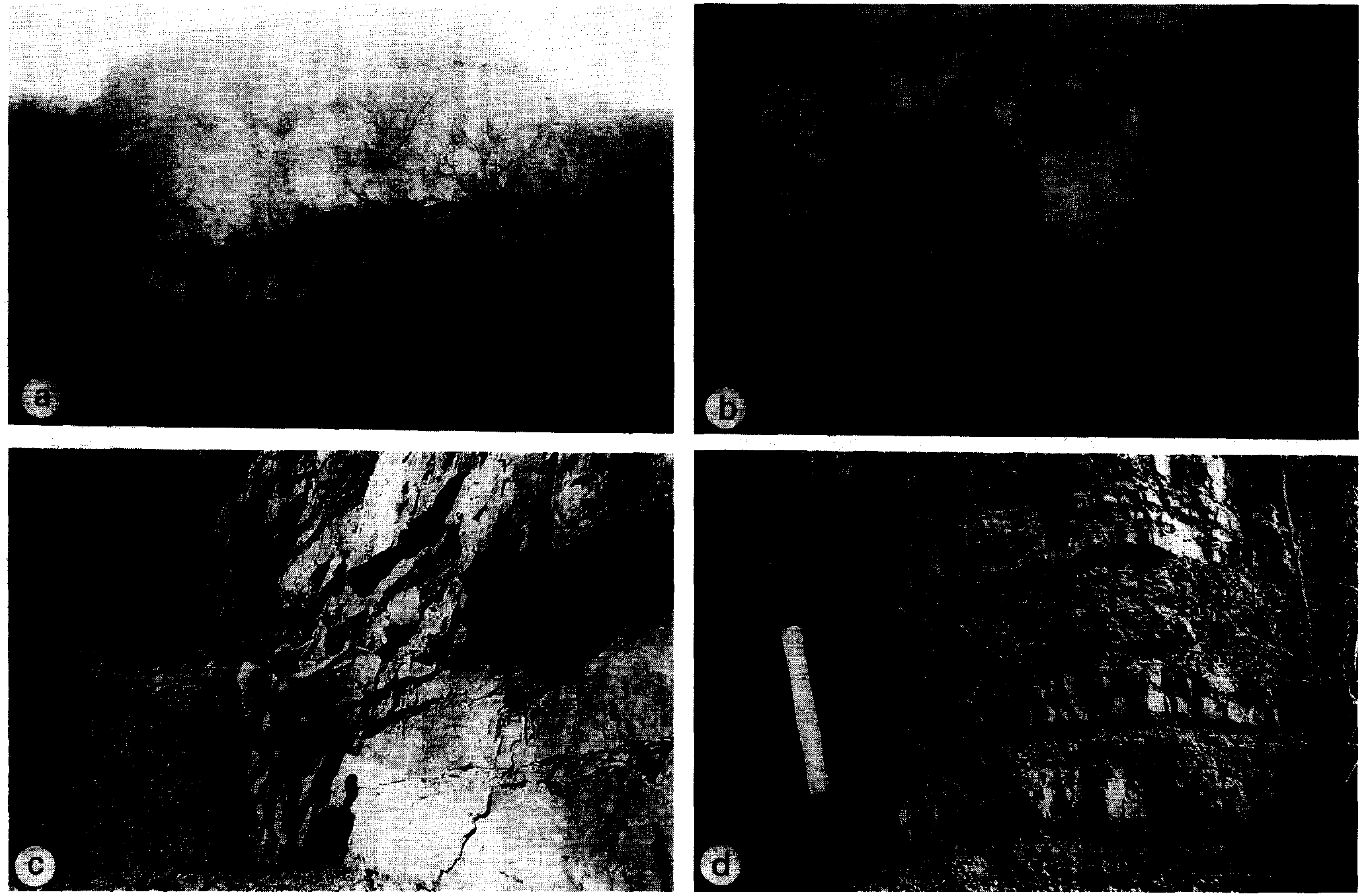


Fig. 18. Photographs of main sediment facies observed in the Pollina and associated sections of Numidian Flysch (External). (a) Very thick-bedded structureless sandstone with large shale clasts and rafts. Note erosion into underlying mudstones. Mistretta section. (b) Detail of (a) near at base. (c) Medium- to thick-bedded sandstone/pebbly sandstones, both structureless and stratified. Note thin shale beds and amalgamation partings. Pollina River section. (d) Thin- to medium-bedded sandstone–mudstone turbidites. Castelbuono section.

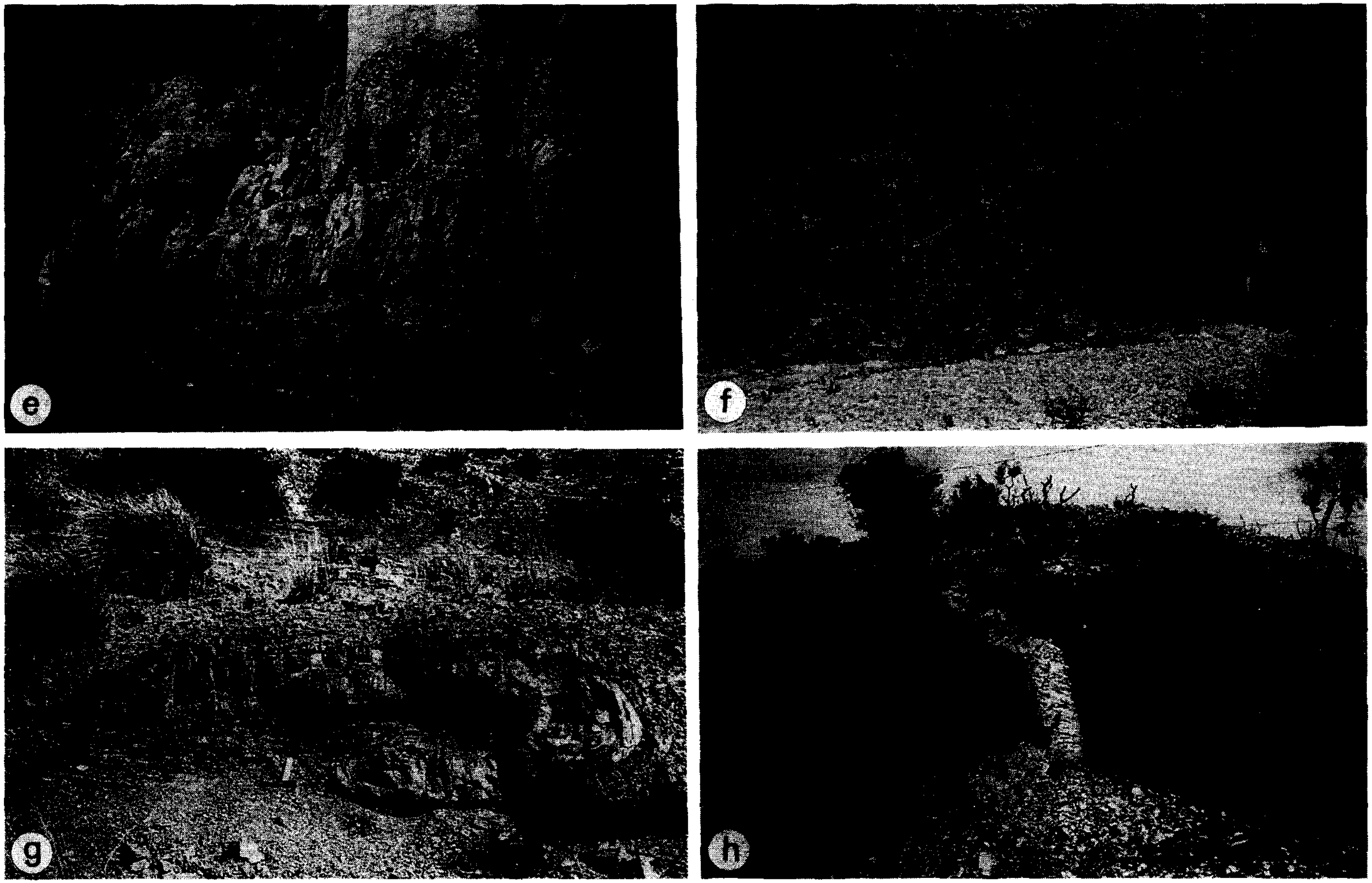


Fig. 18 (continued). (e) Very thick-bedded graded sandstone with sharp erosive base over contorted (slide or load induced) mudstone interval. Note thin and very thin siltstone/mudstone turbidites within mudstone and medium-thick sandstone and pebbly sandstones in upper part of plate. Geraci section. (f) Medium- to very thick-bedded sandstones and pebbly sandstones (various facies) at base of Pollina River section, overlying contorted shale unit with evident slump structures. (g) Detail of overturned slump fold in shale-rich unit below the Pollina village section. (h) Sandstone dyke injected into shale-rich unit adjacent to massive sandstone body near Castelbuono.

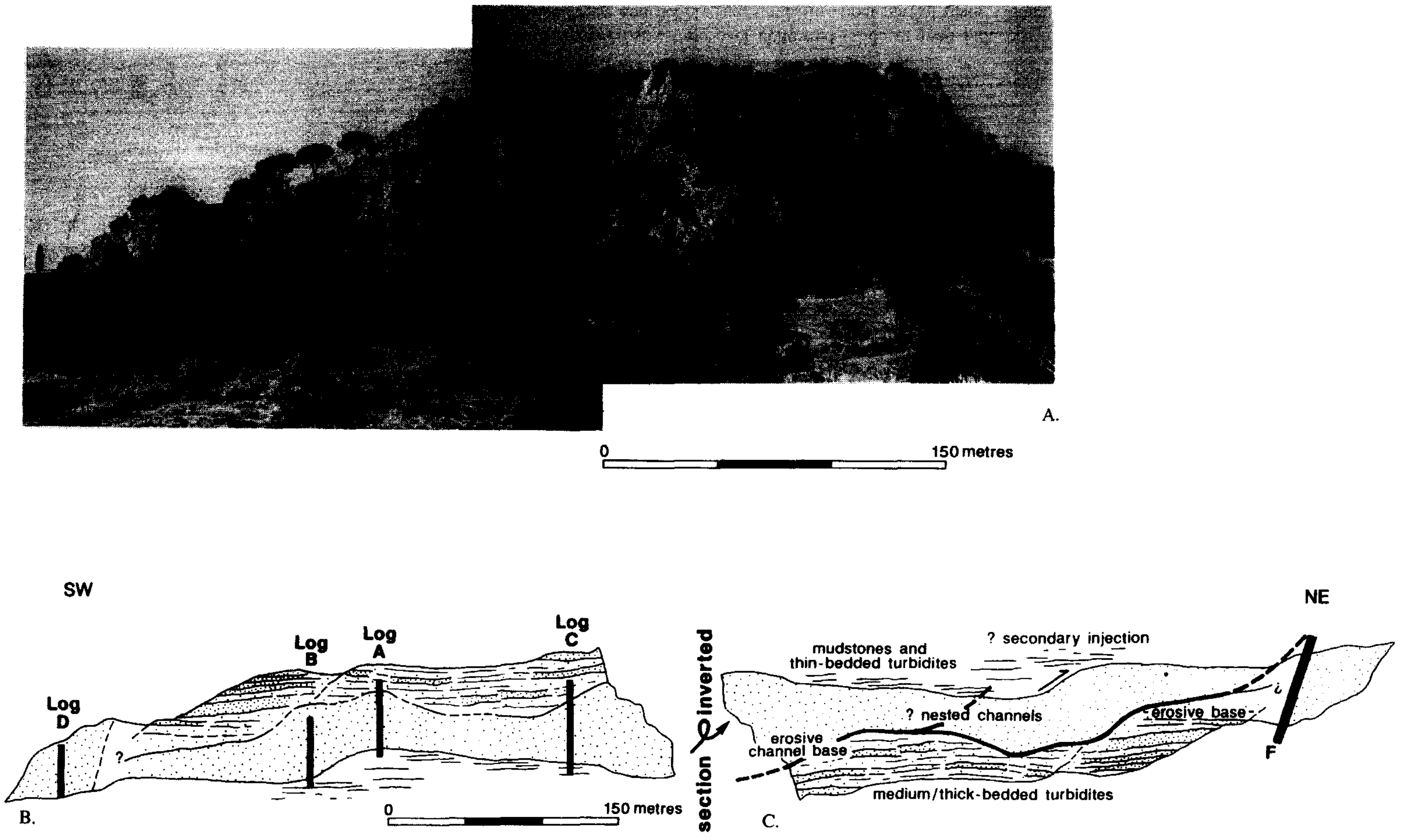


Fig. 19. Photograph (a) and line drawing interpretation of the Contrada di Romano section (stratigraphically inverted). (b) Shows section drawn as seen in photograph, with logged sections indicated. (c) Shows interpretation of channel complex when section has been restored to its right way-up.

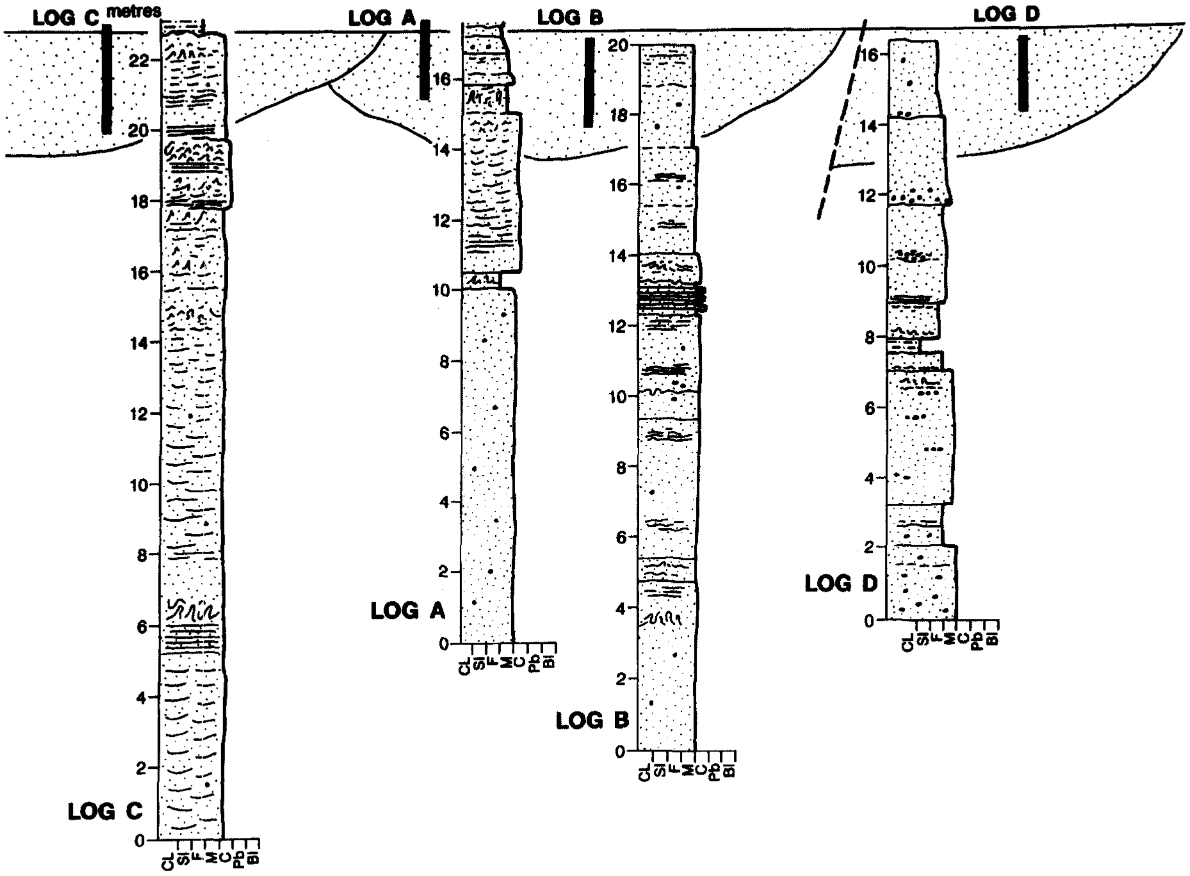


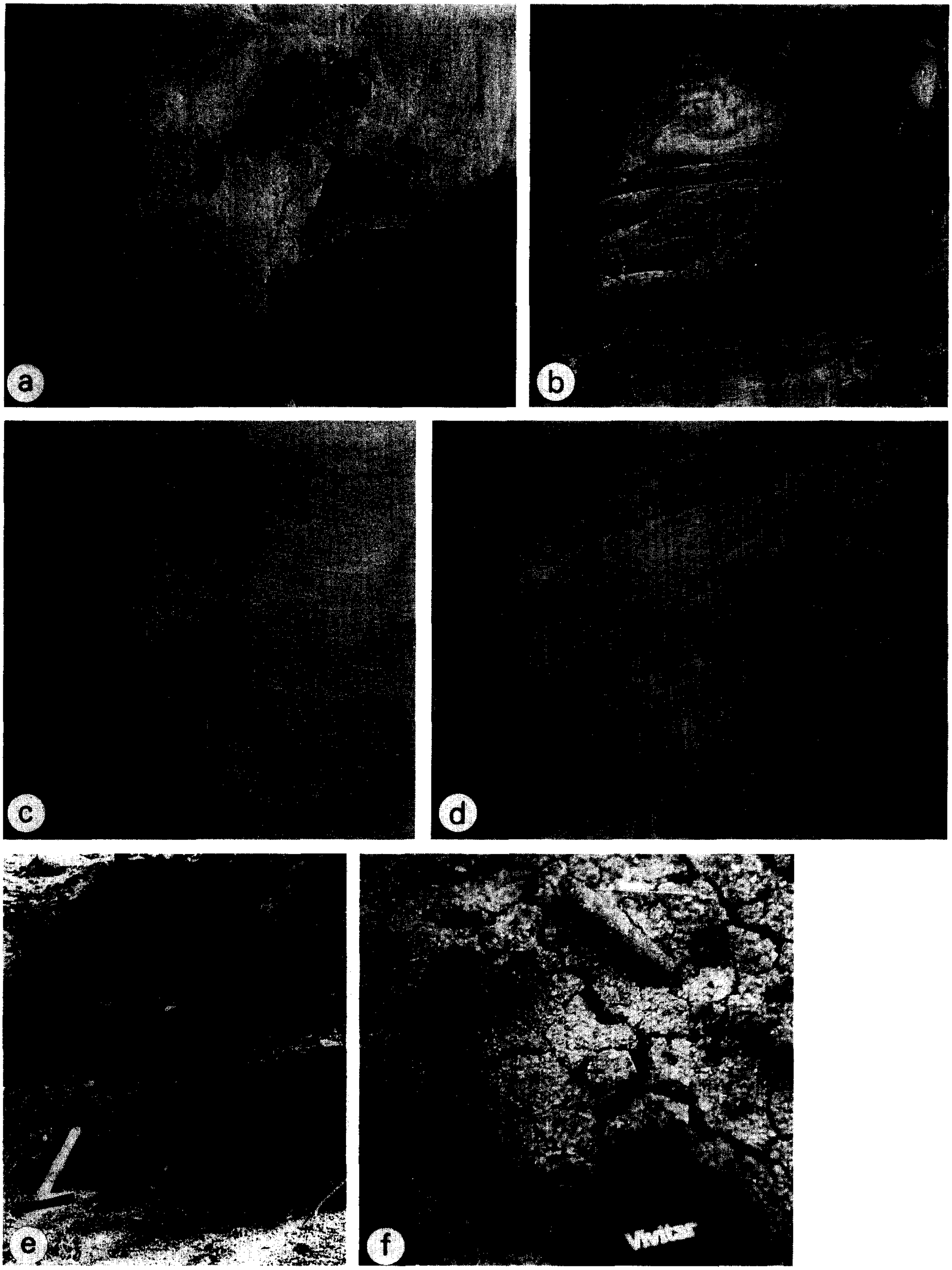
Fig. 20. Detailed graphic logs through the main massive sandstone unit at Contrada di Romano. Location of logged sections shown in Fig. 19.

Table 3
Numidian flysch sediment facies: Contrada di Romano

Massive sandstone facies association	Approx. %
Structureless sandstone (thick- to very thick-bedded)	90
Graded sandstone/pebbly sandstone (thick- to very thick-bedded)	3–5
Stratified sandstone	3–5
Siltstone–mudstone	2
Associated facies	
Sandstone–mudstone units, thin- to thick-bedded	
Silt-laminated mudstones	
Mudstones	
Chaotic sedimentary units (slumped, contorted)	
Cherts and siliceous micrites	
Carbonate turbidites	
Ferromanganese burrowed horizon	
Sandstone dykes (?)	

between the massive sandstone facies association, which represents the coarser-grained sediments of the main bluff, and the associated facies which form the lower-lying surrounds.

The structureless sandstones make up some 90% of the section at Contrada di Romano. They occur in thick to very thick beds, with sharp, erosive or amalgamated contacts. Whereas the individual beds are generally 1–4 m in thickness, amalgamated units of very homogeneous sandstone can be up to 25 m thick. The mean grain size is typically fine to medium sand, with some beds slightly finer- and others slightly coarser-grained. Granules and small pebbles are rare but, where present, give a bimodal grain-size distribution. Sorting is poor to moderate. Water-escape features of all kinds are very common and these are discussed further be-


a
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low (Fig. 21d). The graded sandstones/pebbly sandstones are much less common than the structureless sandstones, and tend to be most obvious as thin granule/pebble bases or fine sandstone/siltstone tops to otherwise thick-bedded massive sandstones. The stratified sandstones generally occur as relatively thin units (10–50 cm thick) separating the massive sandstone units (Fig. 21a–c). Parallel- and cross-stratification are both observed, the latter as wavy, ripple and dune-scale cross-lamination.

Those sediments occurring both below and adjacent to the massive sandstone complex form a generally fine-grained facies association (Fig. 21e). Mudstones, silt-laminated mudstones and chaotic slumped mudstone units are the most abundant facies. These are interbedded with thin- and medium-bedded sandstone–mudstone units that show the typical range of turbidite characteristics, including grading, Bouma sequences, sharp scoured bases, etc. Some of these beds are highly contorted, probably as a result of post-depositional liquefaction; others are more mud-rich, immature turbidites. Thin carbonate (*Nummulites*-rich) turbidites have also been noted and a burrowed, ferromanganese encrusted horizon is evident below the Contrada di Romano section (Fig. 21f).

Irregular massive sandstone bodies (up to 1 m or so in width), poorly exposed within the associated fine-grained facies, are interpreted as sandstone injection features.

6.3.4. Water-escape sequence

The massive sandstones at Contrada di Romano are characterised by a wide range and abundance of water-escape structures. Their presence and type varies both vertically through the section and laterally along the outcrop, and in some parts this variation appears random.

However, a significant number of beds show a more systematic vertical arrangement of water-escape structures, always showing the same sequence of structures from inferred base to top of individual beds. This sequence is illustrated in Fig. 22 and can be described as follows, according to divisions Zi (base) and Zvi (top) (Braakenburg, 1994).

Zi: structureless sandstone over sharp, erosive or amalgamated base;
Zii: sub-parallel/wavy consolidation lamination;
Ziii: shallow, broad, concave-up dishes, ± rare pipes;
Ziv: narrow, (± deep), concave-up dishes, ± pipes;
Zv: pipes and pillars abundant, dishes may be disrupted;
Zvi: pipes, pillars, contorted lamination and burst-through features.

Measurements of dish wavelength and amplitude through a number of sections showing the full or partial Zi–Zvi sequence illustrate clearly this upward trend (Fig. 8).

7. Interpretation

7.1. Depositional setting

We do not comment here on the details of palaeogeographic reconstruction and timing, but rather draw out what we believe to be the most salient points with regard to deposition of the massive sandstone facies association within the Numidian Flysch Formation.

(1) There was an elongate E–W trending basin system parallel to the N African margin, in which individual basins may have been partly or completely isolated. Sediment was fed into these basins in part across the N African slope and in part axially alongslope from west to east.

(2) Basin size is not possible to ascertain with accuracy, but the N–S dimension was likely constrained to, say, a few tens to 100 km and the E–W dimension may have been much greater. Broad slopes may have fed into this narrow trough region from both south and north, but the Sicilian flysch

Fig. 21. Photographs of main sediment facies observed at Contrada di Romano. (a) Two units of very thick-bedded structureless sandstone separated by an interval with parallel- and cross-stratification. (b) Two units of very thick-bedded structureless sandstones (note faint consolidation laminae/broad dishes) separated by more stratified intervals. (c) Very thick-bedded structureless sandstone with consolidation laminae. (d) Detail of water-escape features and burst through zones near top of massive sandstone bed. (e) Shale-rich unit with sandstone turbidites stratigraphically overlying the Contradi di Romano section. (f) Detail of ferromanganese encrusted faecal-pellet burrow casts in Oligocene mudstones.

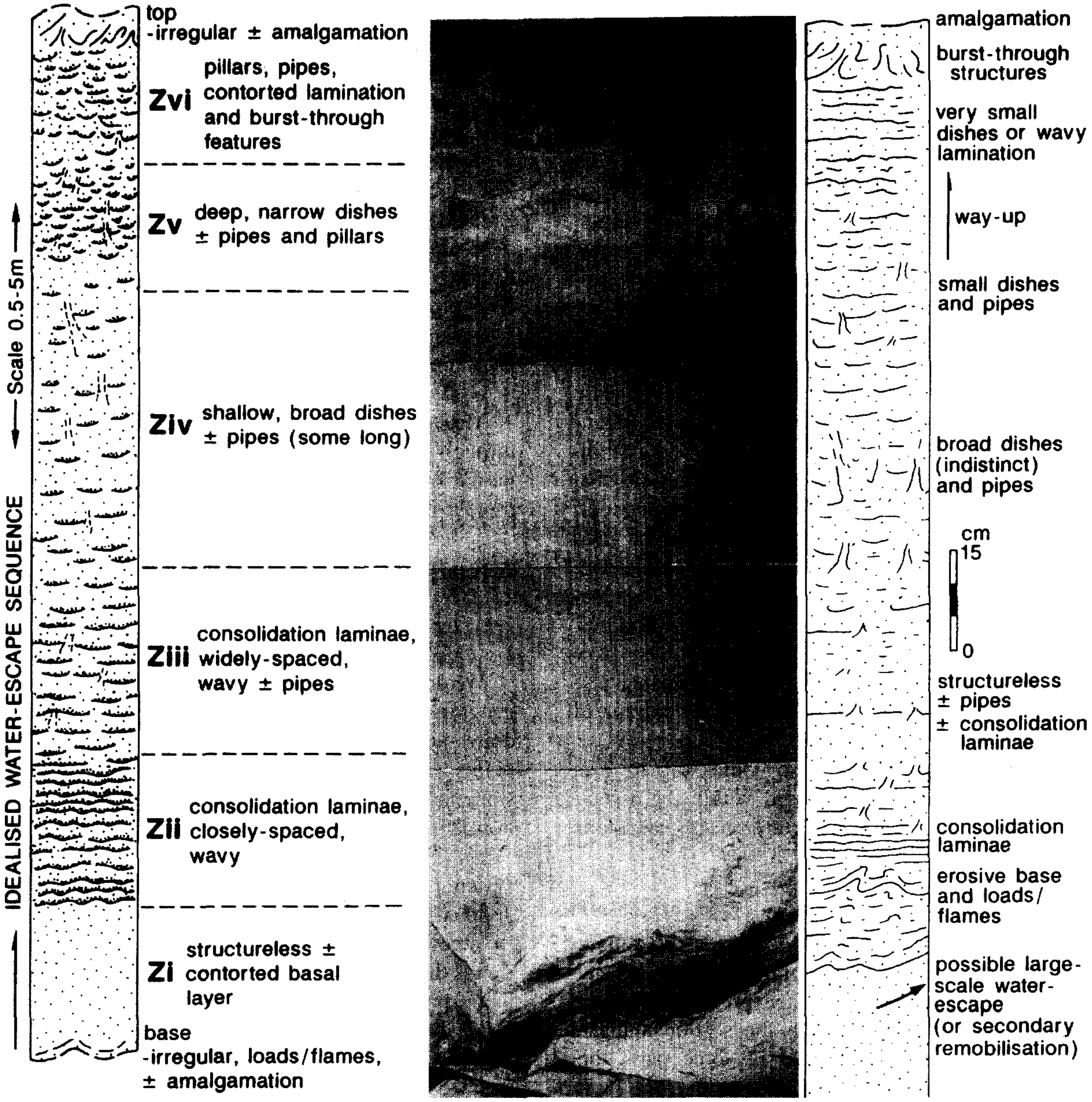

Fig. 22. (a) Example of a massive sandstone bed at Contrada di Romano and graphic representation of the water-escape structures observed. (b) Idealised vertical sequence of water-escape structures (*Zi–Zvi*) as derived, in part, from the Contrada di Romano section.

was most likely derived ultimately from the African craton.

(3) Sediment fill was apparently relatively rapid with over 2 km (up to some 2.5 km in Sicily) accumulating in approximately 5 m.y.: gross average accumulation rates were between 250 and 500 m/m.y. The four sand-rich intervals or 'barres' may have seen deposition rates greatly in excess of this, whilst the intervening mudstones accumulated more slowly.

(4) Tectonic activity was most probably mainly coeval with sedimentation and therefore would have had a pronounced effect on the nature and distribution of the sediment facies. Eustatic sea-level

dropped abruptly at about 30 Ma (Late Oligocene, Chattian) and remained relatively low for the ensuing 10–15 m.y.

(5) The water depth in which the massive sands were deposited is not known. The whole series is turbiditic with no indication of shallow-water features. The composition is dominantly siliciclastic with little calcareous material, in some cases with ferromanganese encrustation on burrow casts. A slope–basinal setting near or just below the CCD may be inferred, with water depths in excess of 2 km. This estimate, however, must remain very speculative.

(6) The overall characteristics of most of the sections examined in Sicily suggest that the massive sandstones were deposited in channel systems that fed across a mud-dominated slope. This interpretation is elaborated below.

7.2. Sandstone geometry

There is strong evidence that the massive sandstone sections examined in all three case studies on the Numidian Flysch (Ponte Finale, Pollina and Condrada di Romano) were deposited in channels. Three channel types/geometries are evident, with the characteristics listed below.

Channel type A — coarse-grained/minor channels:

- estimated width 150–350 m, depth 40–120 m;
- length and sinuosity unknown, but tenuous correlation over 5–10 km;
- scoured, erosive margins, in places stepping down to channel axis;
- minor normal faults now evident at channel margins, probably both synsedimentary and post-depositional in origin;
- internal erosion and channel nesting evident;
- coarse-grained facies association of channel includes pebble conglomerates, shale-clast conglomerates, structureless sandstones/pebbly sandstones ± large floating shale clasts, very thick graded sandstones/pebbly sandstones;
- average sandstone/shale ratio > 9.5 : 1;
- fine-grained interchannel facies dominated by mudstones, siltstones, thin sandstone turbidites, chaotic beds and injected sandstones; no clear levee-type facies;
- occur as isolated channels, nested complexes of 2–3 interconnected channels, and in zones of several channel complexes each separated by several tens to hundreds of metres of encasing mud-rich facies.

Channel type B — coarse-grained/major conduits:

- estimated width 1–3 km (possibly more), depth 250–500 m;
- length and sinuosity unknown, but possible correlation over 15–20 km;
- deeply erosive margins, but typically not fully exposed; major slump units associated with margins;
- channel axis migration over several km laterally and few hundreds of metres upsection evident;
- coarse-grained channel facies association includes range of facies as for (A) but with relatively less conglomerate/shale-clast conglomerate facies and a higher proportion of siltstones/mudstones;
- average sandstone/mudstone ratio ranges from 9.5 : 1 in axial region to 7.5 : 1 laterally;
- fine-grained interchannel facies association as for (A);
- occur as large but isolated main conduit within slope–basin facies association.

Channel type C — massive sandstone/channel plug (?):

- estimated width 0.5 km, depth 50 m;
- length and sinuosity unknown;
- margins obscured, believed erosive;
- channel nesting and internal erosion evident;
- main channel facies are thick- to very thick-bedded structureless sandstones, typically in amalgamated units;
- average sand: shale ratio > 9.5 : 1;
- interchannel facies association as for (A);
- occur as isolated channels (?);
- the principal controls on the channel types developed are the proximality and nature of the sediment source as well as the morphological/tectonic evolution of the conduit zone.

7.3. Facies and processes

The massive sandstone facies association of the Numidian Flysch Formation varies from one section to another. The coastal sections at Ponte Finale and Kalura (Pollina Case Study) have a high proportion of pebble conglomerates, shale-clast conglomerates and very thick-bedded structureless pebbly sandstones. By contrast, the Contrada di Romano section is dominated by very thick-bedded and amalgamated structureless sandstones. Structureless pebbly sandstones and very thick graded beds occur throughout and are particularly characteristic of the Pollina sections.

The main transport mechanisms for these sediments are *high-density turbidity currents* (HDT) associated with probable debris flows and slumping (Stow et al., 1995, 1996). All types of graded bed are observed, but for the thicker units the most common is a thin normally graded top to an otherwise structureless bed, suggesting minor deposition from the waning HDT as it passed on downslope. Rare megaturbidites showing grading over 10^+ m are observed that attest to the large volume of some HDTs. The coarser beds with a higher pebble fraction generally do not preserve dewatering features. In some of the fine- to medium-grained sandstones, there are extensive zones with water-escape structures that indicate rapid deposition from final-stage *modified grain flows*, and rare large-scale cross-lamination that suggests base-of-flow traction.

However, perhaps the most likely origin for the truly structureless sands was either (a) deposition from an inertia flow/grain flow layer beneath a surge-type HDT, or (b) gradual aggradation beneath steady or near-steady flows. Considering the relatively long transport distance inferred from source to depositional site, we favour (b). Amalgamation of different 'events' is evident from field observations, with clear amalgamated sandstone units ranging from 4 m to over 16 m in thickness.

Post-depositional liquefaction and partial remobilisation of the thick sandstone bodies has led to sandstone injection into the surrounding mudstone-rich slope–basin facies.

7.4. Reservoir characteristics

The Numidian Flysch Formation in Sicily is currently an important exploration target, particularly for gas and relatively small discoveries have been made some kilometres to the south of the present study area. Favourable reservoir characteristics include:

- the size, thickness and relative homogeneity of the massive sandstone complex, particularly of the type B channels (described above);
- the very high sandstone/shale ratio;
- the synsedimentary structural control that may have helped to develop suitable traps and also to isolate individual sandstone 'pods';
- the encasing mudstone-dominated series that should act as a suitable seal, and possible source rock;
- the marked absence of any laterally persistent permeability barriers, apart from the shale-clast conglomerates in parts of Channel type A;
- the compositional maturity of the sandstones and the general lack of any extensive carbonate cementation.

The most difficult attributes from the exploration viewpoint must be the complex tectonic setting and nappe emplacement of much of the Numidian series, coupled with the relative isolation of variable-sized channel-geometry reservoirs within a mud-rich succession.

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