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European provenance of the Numidian Flysch in northern Tunisia

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ABSTRACT

The ultimate source of the deepwater Numidian Flysch sediments has long been a matter of controversy. Did the sediments of this late Cenozoic orogenic belt in the western Mediterranean derive from a European or African source, or from a combination of the two? New data presented here strongly favour a European provenance. Zircon ages of 514 ± 19 Ma from Tunisia and 550 ± 28 Ma from Sicily can only have derived from rocks of European affinity. These zircons have been separated from quartz-rich sandstones with a distinctive, highly mature heavy mineral assemblage that is different from those of North African autochthonous formations. The mature petrography and dominance of euhedral prismatic zircon grains indicate a medium to high-grade metamorphic source. Most palaeocurrent data are indicative of flow from the N and NW. The original European provenance is most likely now represented by predominantly metamorphic rocks of the Kabylie belt in northern Algeria, as a result of microplate movement and thrust emplacement.

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Introduction

The Numidian Flysch sedimentary succession comprises part of a complex late Cenozoic orogenic belt that stretches more than 2000 km from mainland Italy, through northern Sicily, across northern Africa and into southern Spain (Fig. 1) (Wezel, 1970; Dewey *et al*., 1989; Hoyez, 1989; Guerrera *et al*., 1993). This widespread turbidite series was deposited in one or several deepwater basins that existed between Europe and Africa during final closure of the Tethys Ocean, between the early Oligocene and the early Miocene (Rupelian to Burdigalian stages). It is generally recognised that in Tunisia, as in most of the orogenic belt, the Numidian Flysch is allochthonous or partially allochthonous and is in thrust contact with the adjacent formations (Rouvier, 1977; El Euchi *et al*., 2004; Riahi *et al*., 2007). Lying south and east of the thrust front, the autochthonous Bejaoua Group, including the Fortuna Sandstone Formation, is coeval in age and comprises shallow marine to fluvial sediments (Yaich *et al*., 2000).

The Numidian system represents a promising petroleum exploration target and is a proven play in Sicily. Excellent exposures of turbidite and related deepwater massive sands (Stow and Johansson, 2000) occur along the northern coast of Tunisia, as well as in stream sections inland, although there is still considerable debate about their ultimate provenance. The Fortuna sandstones, of the autochthonous Bejaoua Group, are considered by some as a potential source for the Numidian Flysch. The Numidian basin and its relationship to the potential source regions are shown in Fig. 2. There are three principal theories:

1. The depositional basin lay to the south of the Alboran microcontinent and north of a calcareous platform region that fringed North Africa. Its wholly terrigenous supply was from the north. Remnants of the Alboran source region remain as the crystalline basement rocks in the Grand Kabylie nappes of northern Algeria, and in parts of Corsica and Sardinia (El Khanchoulfi and Beaudoin, 1990; El Maherssi, 1992; Yaich, 1997).
2. The depositional basin lay to the south of the calcareous platform region, and was supplied from the south, with the Nubian Sandstone of Saharan Africa as the source area and the Fortuna palaeo-delta as the principal supply route (Wezel, 1970; Rouvier, 1977; Hoyez, 1989; Johansson *et al*., 1998; M. Thomas, personal communication 2009).
3. There were two or more principal basins (internal and external flysch), in which case, the direction of sediment supply may have varied between the two (Caire and Coiffait, 1970; Broquet, 1970).

Aim and methods

The principal aim of this study was to address the much-debated question of sediment provenance for the Numidian Flysch and hence to constrain palaeogeography of the west Tethyan regional jigsaw better. Four principal sections along the north coast of Tunisia were logged in detail (Fig. 1B). Over 100 samples of Numidian Flysch sandstones were collected, of which we have processed 66 for petrography, 30 for heavy mineral analysis and three samples for zircon geochronology (Table 1). For comparison, two additional samples were analysed from the Numidian Flysch in Sicily and 12 from the Fortuna sandstones of northern Tunisia (potential provenance). Further details of methods used are provided together with the results.

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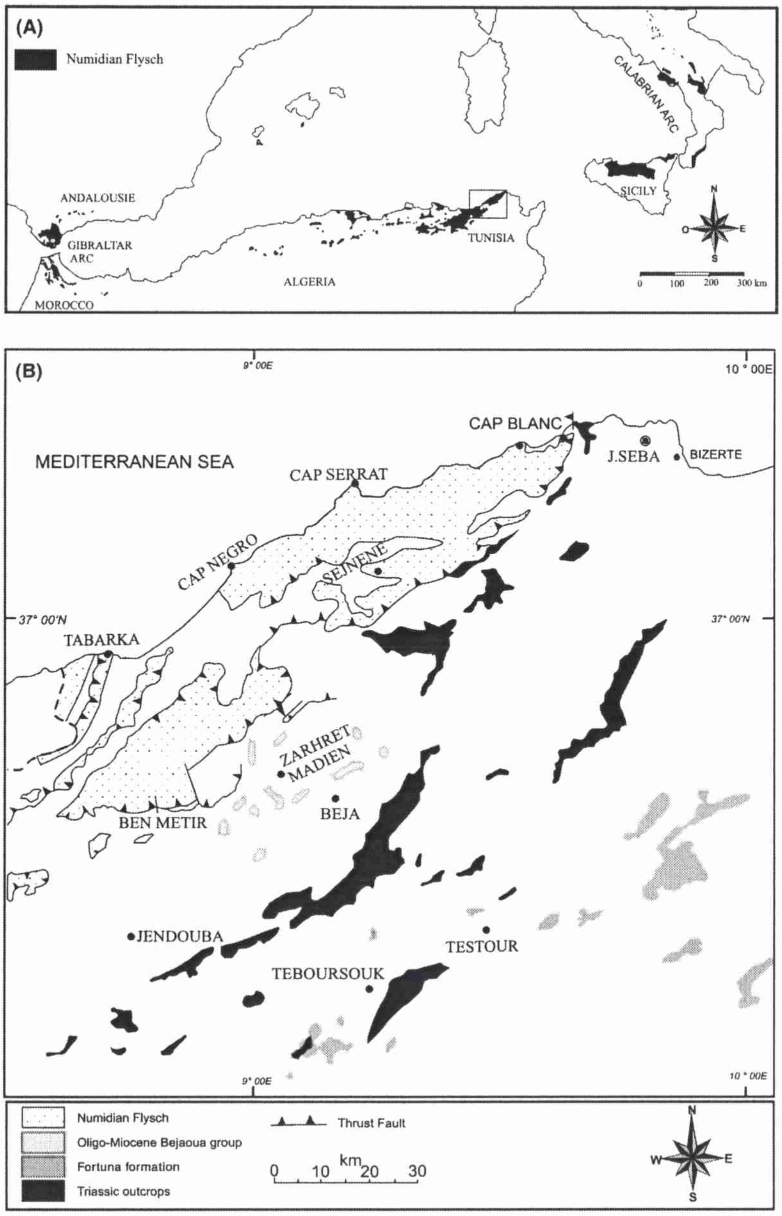


Fig. 1 (A) Location map of Numidian Flysch orogenic belt, western Mediterranean region. (B) Geological summary map of northern Tunisia showing the Oligo-Miocene Numidian Flysch and coeval Bejaoua Group and Fortuna Formation. Sample and section localities named; for sample numbers, see Table 1.

Results

Facies and palaeocurrents

For the Numidian Flysch as a whole, we recognise 15 distinct facies (Facies Groups I–V; Table 2, Fig. 3). At each locality studied, three broad facies associations have been identified. The *deepwater massive sandstone* facies association comprises medium to very thick-bedded massive sandstones, with minor conglomerates, debrites and structured sandstone turbidites. These are commonly associated with injectionite sandstones and occur in blocky sequences, 10–35 m thick, with a sand : shale ratio >9 : 1. The *mudstone–sandstone* facies association is mudstone-dominant, with thin to thick-bedded sandstone turbidites, rare debrites and isolated very thick-bedded lenticular sandstones. Slump-slide units and injectionite sandstones occur locally. There are symmetrical, coarsening-up and fining-up and also random non-sequences, 1–10 m thick at outcrop. The sand : shale ratio is between 1 : 9 and 1 : 4. Still more mud-rich (sand : shale ratio < 1 : 9) is the *mudstone* facies association, comprising mud-rich facies of hemipelagites and fine-grained turbidites, with rare thin-bedded sandstones. These are also commonly associated with slump-slide units and more rarely with injectionite sandstones. Random or non-sequences are common, with possible small-scale compensation cycles.

Field measurements yielding *palaeocurrent data* were gathered from all Numidian Flysch localities studied (Fig. 4). The mean of flute and ripple measurements gives dip-corrected flow towards E or SE, which concurs with numerous groove measurements (orientation but not sense), but there is significant variation around this mean in some areas.

Sandstone petrography

The Numidian Flysch sandstone mineralogy is based on petrographic study of 66 samples, point-counting 200–400 grains per thin section. Most fall in the pure quartzarenite field (>90% quartz) of Stow (2005, modified after Pettijohn *et al.*, 1987), with a few samples of feldspathic arenites (80–90% quartz, 3–7% feldspar, 1–5% mica). The heavy mineral fraction is notably high – from 2% to 7%. Calcite and authigenic dolomite are only present locally in samples from Sicily. Although the sandstones show high mineralogical maturity, they are texturally mature to sub-mature in character.

Whereas unicrystalline quartz is the dominant form (46–83%), polycrystalline quartz is common in coarse-grained sandstones and sandy conglomerates, as it generally has a larger grain size (~2 mm). These include grains with sub-equant intergrowths and moderate lattice strain, as well as those with more attenuated, gneissose fabrics or in which sub-crystals have been partially

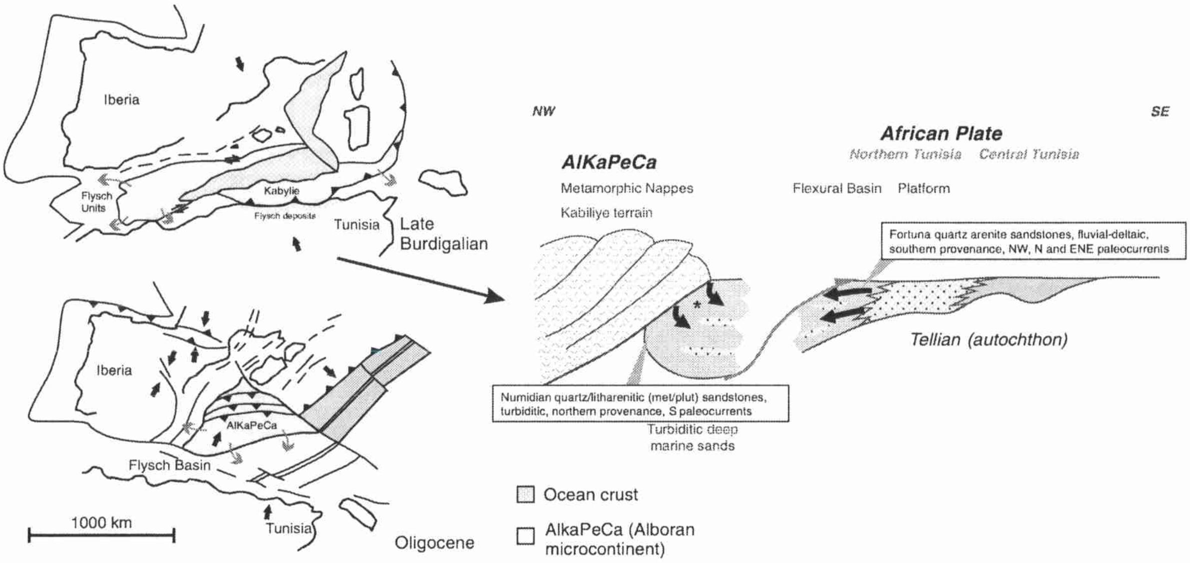


Fig. 2 Plate tectonic reconstruction for part of the western Mediterranean region modified after Lonergan and White (1997). The Oligocene reconstruction shows the location of the Numidian Flysch basin between the Alboran microcontinent (AlKaPeCa) and North Africa. Sediment was supplied to this basin either from the north (this article) or from the south, or from a combination of the two. The Late Burdigalian (early Miocene) reconstruction and schematic cross-section show thrust emplacement of the Alboran microplate (as the Kabylie Range) and associated Numidian Flysch onto the North African margin.

Table 1 Samples used for analytical programme, indicating location, facies group (see Table 2) and analytical methods used (P, petrography; HM, heavy mineral analysis; Z, zircon geochronology).

Sample	Location	Facies group	Analytical methods
1	Tabarka	Massive sand	P, HM
2	Tabarka	Massive sand	P
8	Tabarka	Massive sand	P
20	Tabarka	Structured sand	P, HM
22	Tabarka	Structured sand	P
23	Tabarka	Structured sand	P
29	Tabarka	Structured sand	P, HM
32	Tabarka	Structured sand	P, HM
34	Tabarka	Structured sand	P
36	Tabarka	Massive sand	P
37	Tabarka	Massive sand	P, HM
41	Tabarka	Structured sand	P, HM
42	Tabarka	Massive sand	P, HM
43b	Tabarka	Conglomerate	P
43	Tabarka	Conglomerate	P, HM
44	Tabarka	Conglomerate	P
46	Tabarka	Chaotica	P
47	Tabarka	Chaotica	P, HM
50	Tabarka	Massive sand	P
54	Tabarka	Structured sand	P, HM
56	Tabarka	Structured sand	P
58	Tabarka	Massive sand	P, HM
59	Tabarka	Massive sand	P
60	Tabarka	Massive sand	P
63	Tabarka	Massive sand	P, HM
65	Tabarka	Massive sand	P, HM
DS1	Testour	Fortuna formation	P
DS2a	Testour	Fortuna formation	P

re-assimilated at elevated temperatures. Some quartz grains show inclusions of rutile needles and zircons. The feldspars are all alkali feldspars, including both orthoclase and albite, and the mica fraction is wholly muscovite. Rock fragments are very rare.

Heavy mineral data

Heavy mineral separates for 30 representative samples were prepared as grain mounts (63- to 250-micron size fraction) and studied using a ribbon-counting method of 200–400 grains per sample. Typically, the heavy mineral fraction of the Tunisian Numidian Flysch comprises approximately equal proportions of non-opaque and opaque minerals (mainly iron oxides) (Fig. 5). The non-opaques are dominated by tourmaline and zircon, with a lesser proportion of rutile. Accessory heavy minerals include rare garnet and anatase (generally present), and very rare piemontite, monazite, titanite, apatite, staurolite, glauconite and chlorite (present only in some samples).

Zircons are the most common non-opaques. They are colourless with extremely high relief and present as a mixture of two different types. In the

Table 1 (*Continued*)

Sample	Location	Facies group	Analytical methods
DS2b	Testour	Fortuna formation	P
DS3	Testour	Fortuna formation	P
DS4	Testour	Fortuna formation	P
DS6	Tabarka	Structured sand	P, HM
DS7	Tabarka	Structured sand	P, HM
DS8	Tabarka	Massive sand	P
DS8a	Tabarka	Massive sand	HM
DS9	Tabarka	Chaotica	P
DS10a	Tabarka	Chaotica	P, HM
DS10b	Tabarka	Massive sand	P, HM, Z
DS12	Tabarka	Massive sand	P
DS13	Tabarka	Massive sand	HM
DS15	Tabarka	Massive sand	P, HM
DS16	Tabarka	Chaotica	P
DS17	Tabarka	Massive sand	P
DS18	Tabarka	Massive sand	P
DS19	Tabarka	Massive sand	P
DS20	Tabarka	Massive sand	P, HM
DS21	Tabarka	Massive sand	P
DS22	Tabarka	Structured sand	P
DS23	Tabarka	Massive sand	P
DS24	Babouche	Massive sand	P
DS25	Sousa	Structured sand	P
DS26	Sousa	Structured sand	P
DS28	Jebel Gassa	Structured sand	P
DS29	Jebel Gassa	Massive sand	P
DS31	Cap Serrat	Massive sand	P, HM
DS32	Cap Serrat	Structured sand	P
DS33	Cap Serrat	Conglomerate	P, HM
DS34	Cap Serrat	Massive sand	P, HM
DS35	Cap Serrat	Structured sand	P
DS36	Cap Serrat	Massive sand	P
DS37a	Cap Serrat	Massive sand	P
DS37b	Cap Serrat	Massive sand	P
DS45	Ras el Koran	Massive sand	P, HM
DS45f	Cap Blanc	Massive sand	P, HM
Pollina	Sicily	Massive sand	P, HM
Romano	Sicily	Massive sand	P, HM, Z
Fortuna	Testour	Fortuna formation	P, HM, Z

Tunisian samples, approximately 20% of the zircons are small (on average 0.08 mm) and rounded, whereas approximately 80% are euhedral, prismatic and larger in size (maximum of 0.18 mm). Tourmalines are the second most abundant non-opaque heavy mineral observed. These are blue/green, have colour zoning, polarisation bands and typically exhibit pleochroism. They are mostly subhedral in shape, some more anhedral, but rarely euhedral. Grain size is variable from 0.08 to 0.40 mm. Rutile is the third most abundant non-opaque. It occurs in shades of red, brownish red and amber, with very high relief and distinctive pleochroism.

The mineralogical maturity of heavy mineral assemblages is defined by the zircon–rutile–tourmaline (ZRT) index, which is the ZRT proportion of the non-opaque heavy fraction. In the Tunisian Numidian Flysch, the ZRT index is very high (between 25 : 1 and 30 : 1), whereas in both the Sicily Numidian and the Tunisian Fortuna formations (the latter represents the potential North African source), the ZRT index is lower as a result of a relatively high calcite and/or dolomite fraction. Triangular plots of the ZRT assemblages, recalculated to 100% and compared with published data, are shown in Fig. 6. These emphasise the differences in average values between the Numidian Flysch of Tunisia (45 : 15 : 40) and Sicily (47 : 12 : 41), on the one hand, and the Fortuna of Tunisia (70 : 12 : 18), on the other. The Fortuna samples are also notably higher in Opaque : ZRT ratio and in the ubiquitous presence of a calcite/dolomite fraction (Fig. 5).

Zircon dating

Some 60 zircon grains were separated from a representative pilot suite of three samples from the Fortuna Formation and from the Numidian Flysch in Sicily and Tunisia. The larger, more euhedral grains were selected for U–Pb analysis with a VG Elemental PQ2 + ICP–MS coupled to a 193-nm excimer laser, using a method adapted from Hirata and Nesbitt (1995) and Iizuka and Hirata (2004). The zircon samples were calibrated against zircon 91500 (Wiedenbeck *et al.*, 2004). Corrected $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ratios have been plotted onto U/Pb concordia diagrams using the program *Isoplot* (Ludwig, 2003) and the results are shown in Fig. 7.

The Numidian Flysch zircons from Tunisia fall on the concordia line, suggesting fresh zircon grains, with a mean age of 514 ± 19 Ma. Those from Sicily also fall on the concordia line, showing comparable freshness and a mean age of 550 ± 28 Ma. The zircons from the Fortuna Formation (Tunisia), however, plot below the concordia line, which indicates a loss of lead. This generally occurs for zircons that are older, and have likely been subjected to different phases of sediment reworking and weathering. These zircons all give similar ages (mean 1698 ± 67 Ma), significantly older than any of the Numidian Flysch zircons.

Discussion: The Provenance Debate

The principal facies and facies associations of the Numidian Flysch in northern Tunisia, together with their patterns of vertical and horizontal distribution (Riahi *et al.*, 2007, 2009; Stow *et al.*, 2009) are most compatible with a slope-centred depositional system (mud-dominated), locally cut by downslope channels (sand-dominated) (Stow *et al.*, 1996). This compares closely with earlier interpretation of the Numidian Flysch in Sicily (Stow *et al.*, 1999; Stow and Johannson,

Table 2 Principal sediment facies and facies groups for the Numidian Flysch Formation, Northern Tunisia. See text for their occurrence in distinct facies associations.

Group I: Conglomerate facies
F1: Thin to thick-bedded, lenticular-parallel sided, fine-medium conglomerate
Process interpretation: probable high-density turbidites
Group II: Massive sandstone facies
F2: Thick to very thick-bedded, structureless massive sandstone
F3: Thick to very thick-bedded, massive sandstone with water-escape structures
F4: Thick to very thick-bedded, massive sandstone with minor grading/structures
(All massive sandstone facies are lenticular to parallel-bedded, and with/without shale clasts, amalgamation horizons, basal loading and scouring, rare cross-stratification and rare bioturbation)
Process interpretation: mainly high-density turbidites and sandy debrites
Group III: Structured sandstone facies
F5: Thick to very thick-bedded, graded sandstone (Bouma/Lowe turbidite sequences)
F6: Medium to thick-bedded, graded sandstone (Bouma turbidite sequences)
F7: Thin to very thin-bedded graded sandstone (Stow/Bouma turbidite sequences)
F8: Thick-to-thin-bedded, cross-stratified sandstone
(All structured sandstone facies are lenticular to parallel-bedded, and with/without basal loading and scouring, turbidite structural sequences, water-escape structures and bioturbation)
Process interpretation: mainly medium to low-density turbidites
Group IV: Mudstone & siltstone facies
F9: Mudstone with graded, silt-laminated units (Stow turbidite sequences)
F10: Extensively bioturbated and burrowed mudstone/calcareous mudstone
(All mudstone/siltstone facies occur in very thin to very thick units, typically without distinct bed boundaries)
Process interpretation: low-density turbidites and hemipelagites
Group V: Chaotica facies
F11: Chaotic units with large to small-scale soft-sediment folds
F12: Chaotic sand-rich units with clasts, including soft-sand clasts
F13: Chaotic mud-rich units with clasts, including soft-sediment clasts
F14: Chaotic shale-clast conglomerates
F15: Chaotic injectionite sands – bed-parallel to perpendicular
(Chaotica facies occur in variable bed and unit thicknesses)
Process interpretation: F11 – slump-slide deposits; F12, 13, 14 – debrites; F15 – injected sand bodies

2000). The thick channel sand bodies are generally associated with sandstone injection into the surrounding lithologies, as noted also by Parize and Beaudoin (1986). In other cases, some of the interbedded sandstone and sandstone–mudstone facies associations are better interpreted as lobe deposits. This interpretation of depositional setting is fully compatible with most previous work on the Numidian, and specifically that in Tunisia (El Maherssi, 1992; Yaich, 1997; Riahi *et al.*, 2007). Furthermore, our data on *palaeocurrent directions* are generally in agreement with earlier studies in suggesting supply from the N or NW directed towards the S or SE.

Petrographic data from northern Tunisia show compositionally mature quartzarenitic sandstones, including polycrystalline quartz of probable medium to high-grade metamorphic origin. The mineralogical data point to a provenance comprising sedimentary and metamorphic/plutonic rocks. Although this is of cratonic type according to Dickinson's (1985) diagram for petrographic determination, it is equally compatible with erosion of an orogenic belt. There is a further likelihood of multiple cycles of erosion–deposition through sedimentary successions.

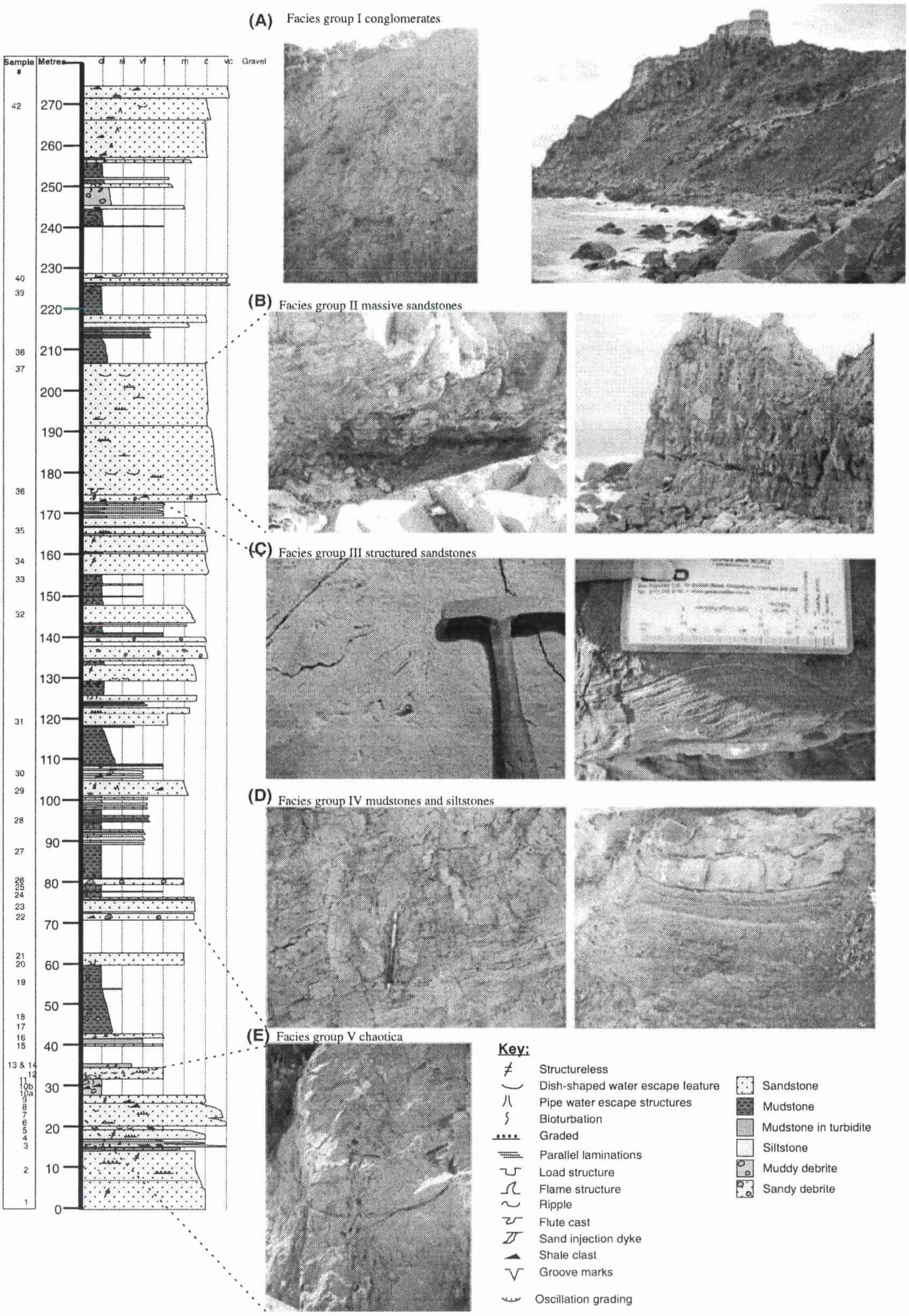
Heavy Mineral data show a dominant ZRT assemblage, which is well known as an ultrastable component of sedimentary rocks, often indicative of multiple cycles of erosion–deposition. Zircon is regarded as one of the most stable minerals and is a widespread accessory mineral in rocks of crustal origin. Tourmaline crystallises in granites, granite pegmatites and in contact or regionally metamorphosed rocks, and is widespread in all types of detrital sediments. Rutile is also common in detrital sediments, and originally derived from high-grade regionally metamorphosed terranes.

The rare and very rare heavy minerals present include garnet, piemontite, chlorite, apatite and staurolite, all of which are most common in a variety of metamorphic rocks, mainly medium and high grade. Anatase is found in both igneous and metamorphic rocks, whereas monazite is an accessory mineral of granitic rocks and also a rare constituent of metamorphic schists, gneisses and granulites.

There is a close correspondence across the Numidian Flysch of Northern Tunisia in both ZRT ratios and heavy mineral assemblages, and also very similar values obtained from the Numidian Flysch samples from northern Sicily. This is strong evidence of a similar provenance. The Fortuna Formation, however, has a different ZRT relationship from that of the Numidian Flysch of either Sicily or Tunisia. The Fortuna samples are also notably higher than the Numidian Flysch in opaque : ZRT ratio and in the ubiquitous presence of a calcite/dolomite fraction. Although this further underlines the likely difference in provenance and is in agreement with Yaich (1997), the evidence remains equivocal. This is because the opaque minerals appear to be dominated by iron oxides, many of which are likely to be weathering products formed through oxidation of other Fe-bearing minerals. Furthermore, calcite and dolomite may indicate either a local additional source, or the product of weathering, cementation and authigenic formation.

Zircon dating has provided very significant results. The Tunisian and Sicilian Numidian Flysch zircons give ages similar to one another: the mean zircon age from Tunisia is 514 ± 19 Ma and that from Sicily is 550 ± 28 Ma. These ages compare well with the *c.* 505 Ma Rb/Sr age reported by Bossière and Peucat (1986) for basement rocks in the Kabylie nappe zone. Zircon ages of 500–600 or 200–300 Ma are considered most likely to indicate a European provenance, whereas much older ages (around 2000 Ma) indicate derivation from the African craton (Lancelot *et al.*, 1977).

The Kabylies is one of the inner zones of the Maghrebides, which are part of the peri-Mediterranean belt of late Tertiary age that delimits the African and European plates. They were most likely emplaced during the 40–15 Ma time span as a result of the



(A) Facies group I conglomerates

(B) Facies group II massive sandstones

(C) Facies group III structured sandstones

(D) Facies group IV mudstones and siltstones

(E) Facies group V chaotica

Fig. 3 Sedimentary log through 275 m of section at Tabarka (Citadel section shown in top right image). Photographs show typical examples of the principal facies groups recognised. Sample numbers indicate location of samples taken from the Tabarka Section.

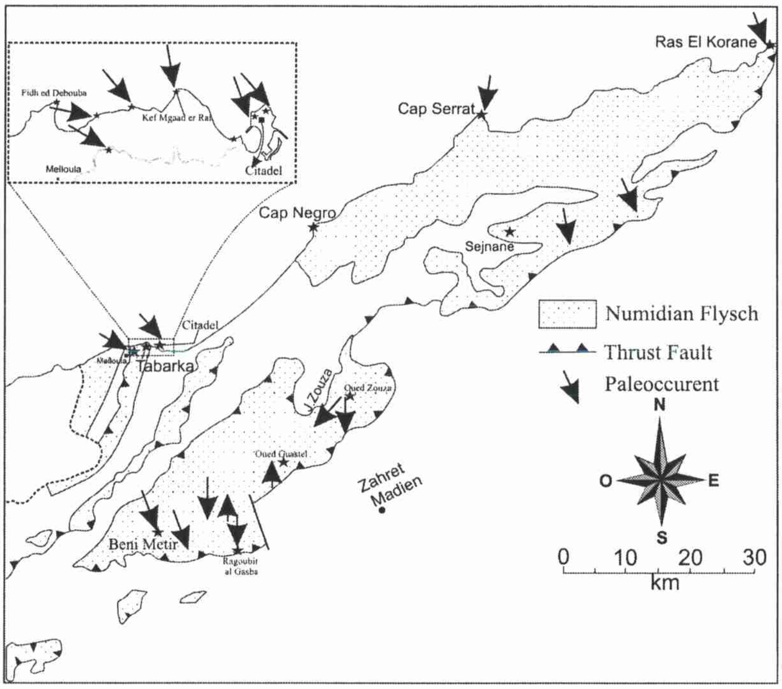


Fig. 4 Summary of palaeocurrent data from Numidian Flysch across northern Tunisia. Each arrow indicates the mean flow direction from 10 to 30 measurements at that locality.

underthrusting of the North African margin beneath the Alboran plate. The Kabylies are now mainly represented by inliers of crystalline rocks surrounded by Oligo-Miocene and younger sediments. Pre-Oligocene reconstructions locate the Kabylies at > 700 km NNW from their present day location (Hammor *et al.*, 2006) – i.e. in southern Europe, probably as part of the Iberian plate.

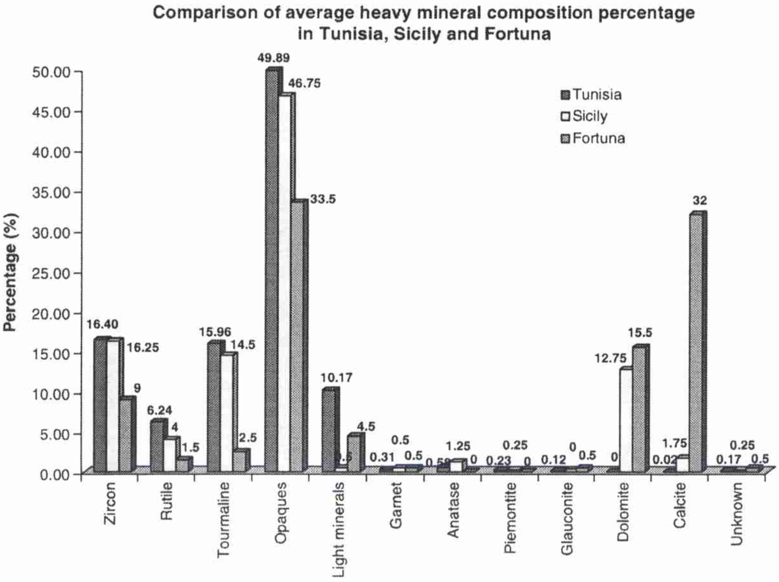


Fig. 5 Histogram showing average heavy mineral abundances for all samples analysed in this study. Comparison between the Numidian Flysch from northern Tunisia and Sicily, and the Fortuna formation of northern Tunisia.

Prior to this study (to our knowledge), there has been only one radiometric date reported for the Numidian Flysch in Tunisia, giving a zircon age of 1750 ± 100 Ma (Gaudette *et al.*, 1975; abstract only). This has then been reported in a number of subsequent studies as supporting an African provenance. However, with no published information on the sample type and location, or on the separation and dating methodology, we believe that this age result should be treated with caution. Lancelot *et al.* (1977) studied zircons from the Numidian Flysch and coeval successions from southern Italy and Spain. The zircon dates they obtained (1350 and 550 Ma) present somewhat conflicting evidence, and from their study of zircon morphology, they propose a dual provenance – an African source for the well-rounded zircons and a European source for the euhedral prismatic variety. Interestingly, as indicated above (results), our data from Tunisia show 80% well-formed, prismatic zircons, which would support a northerly provenance for the Numidian Flysch in this region.

Zircon ages (1698 ± 67 Ma) from the Fortuna Formation differ greatly from those for the Numidian Flysch, and are most compatible with a provenance from the African craton in the south, followed by recycling through the Nubian Sandstone and the Fortuna Delta. The Fortuna Formation also shows petrographic differences from the Numidian Flysch in terms of ZRT abundances. There appears to be no direct link between the two successions and hence we would conclude that they have different provenance.

In summary, the weight of evidence clearly favours a European rather than African terrane as the most likely provenance for the Numidian Flysch in Tunisia. This evidence includes palaeocurrent data indicative of flow from the N and NW, petrographic characteristics most compatible with a medium to high-grade metamorphic terrane, a distinctive and highly mature heavy mineral assemblage different from those of the Fortuna Formation in Tunisia, a dominance of

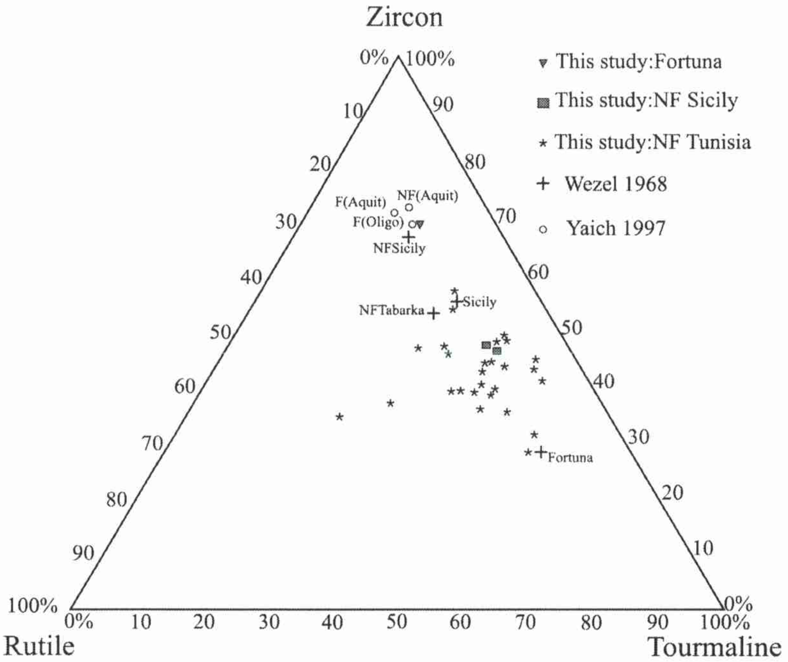


Fig. 6 Zircon–rutile–tourmaline (ZRT) triangular plot showing average values for the different localities examined in this study, together with selected data reported by Wezel (1968) and Yaich (1997).

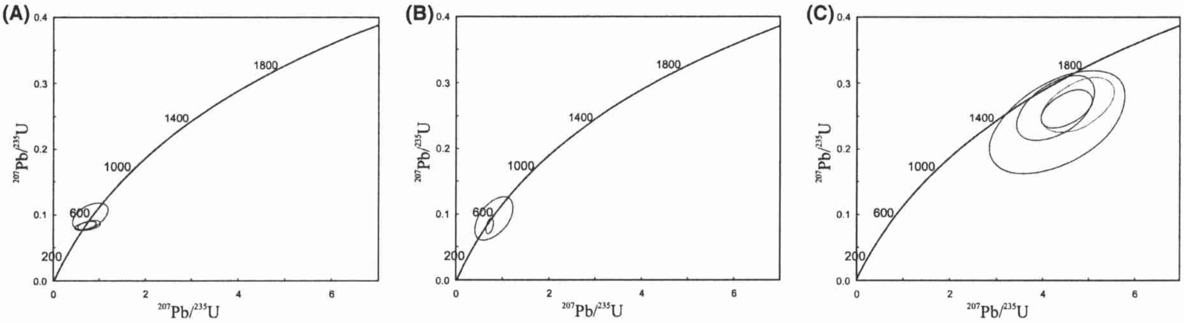


Fig. 7 Zircon geochronology. U–Pb Concordia diagrams showing the ages of zircons. (A) Numidian Flysch, Tunisia = 514 ± 19 Ma; (B) Numidian Flysch, Sicily = 550 ± 28 Ma; and (C) Fortuna Formation, Tunisia = 1689 ± 67 Ma. Data point error ellipses are 68.3% confident.

euhedral prismatic zircon grains and zircon radiometric dates with strong European affinity. However, it is clear that a more extensive study of zircon morphology and geochronology is required across North Africa to test these preliminary findings and to reveal any basin compartmentalisation within the Numidian Flysch.

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