Terra Nova

REPLY

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Reply to comment on 'European provenance of the Numidian Flysch in northern Tunisia'

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The Numidian Flysch is a major sedimentary succession that straddles the two distinct tectonic plates of Africa and Eurasia. Its accumulation during parts of the Oligocene and Miocene epochs represents an important phase in the tectonic development of the region, marked by basin formation and active sedimentary fill during the continued closure of the Tethys Seaway. It reservoirs a producing gas field in the subsurface of Sicily and is the subject of active oil exploration offshore in the western Mediterranean region. However, it is a complex succession and there are many questions remaining, including that of its ultimate provenance.

In our recent paper (Fildes *et al*., 2010), we presented new data on the Numidian Flysch of northern Tunisia and argued that these provided good evidence for an original European provenance. The data were certainly preliminary in nature, with more analyses currently in progress, and there is clearly still room for debate. We therefore welcome the comment on our paper by Thomas *et al*. (2010a), based on previously published zircon geochronology data. We further acknowledge their excellent and more substantial review recently published (Thomas *et al*., 2010b), which also promotes an African provenance for the Numidian Flysch.

However, having carefully considered their review of the literature on zircon dating, we are inclined to maintain our interpretation of a northern (European) provenance. We take this opportunity, therefore, to reinforce our earlier arguments, to introduce some new data and to propose further lines of research that we suggest will produce fruitful results in the future.

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Combined evidence

As with most areas of geology, the best and most reliable interpretations are made by considering *multiple* datasets rather than one alone. In this case, the combination of evidence we believe is very strong and includes the following.

Palaeogeographic reconstruction

All tectonic reconstructions place the Numidian Flysch basin (or series of basins) somewhere between Europe and North Africa. We know from previous biostratigraphic studies and from our own recent work (Riahi *et al*., 2010a; 2010b) that the principal sedimentary fill took place from about 35 to 20 Ma, and that final thrust emplacement was around 15 Ma. It is reasonable to assume that, during this time, the basin was moving southwards in front of the European crustal block (the so-called AlKaPeCa domain) – let us say at a relatively slow average rate of spreading/emplacement of 2–3 cm year^{-1}. This would therefore result in a net southward movement of between 400 and 600 km over a 20 Ma period. Such a distance is similar to the maximum width of the western Mediterranean Sea today, so that at least the *early* basin fill would have been a long way from any African supply system.

It is possible that as convergence continued and the Numidian Basin approached northern Africa, there would have been potential for additional supply from an African source during the *late* stages of basin fill. However, as the foredeep portion of the foreland basin is occupied by an immature Mauritanian Flysch system of similar age, the Numidian Flysch should have been confined to the backdeep (or back-bulge) region to the north of a fore-bulge high. Both the fore- and back-bulge areas of foreland basins are typically of shallow-water affinity and unlikely, therefore, to be depositional sites for a thick succession of deep-water turbidites.

Coastal barrier

Other work is currently underway at the University of Tunis on the equivalent-age rocks immediately south of the Numidian Flysch thrust front in northern Tunisia. These are represented by: (i) coarse-grained, mineralogically immature siliciclastics of the fluvial–deltaic Fortuna Formation (as mentioned in Fildes *et al*., 2010); (ii) shallow-marine carbonates of various lithofacies; and (iii) minor glauconitic sandstones of shallow-marine affinity. Locally, the carbonate and glauconitic sandstones appear to have accumulated on a relative tectonic high (perhaps the fore-bulge region mentioned above) and therefore to have acted as an effective barrier to sediment supply from the Fortuna delta. Of course, we accept the proposition of Thomas *et al*. (2010a,b) that supply to the Numidian Flysch basin could have been in part longitudinal, from further to the west for example.

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Fluvio-deltaic supply

There is little doubt that the volume of sediment represented by the Numidian Flysch formation, even that of northern Tunisia alone, requires prolonged input from a major sediment supply route – presumably one or more fluvio-deltaic systems. The *only* one known from northern Africa is the Fortuna system, which is why it has been implicated as the principal supply route by proponents of a North African provenance. However, the combined data presented (above and below) militate against the Fortuna, as accepted by Thomas *et al.* (2010a,b). They therefore invoke lateral supply from Algeria in the west and assume that all evidence of the major fluvio-deltaic supply system has been removed by subsequent erosion. This seems to us to be an unnecessarily complex explanation.

Palaeocurrent directions

The data we presented are difficult to ignore completely and represent a compilation of our own observations and those reported in the literature. They very dominantly show a north–south directed supply route. Certainly there are local variations from this norm, exactly as one would expect in any sedimentary system – indeed, we might have anticipated a still more diverse pattern. Large-scale uniform rotation of the entire emplaced succession, by at least 50 degrees as proposed by Thomas *et al.* (2010b), once again seems unnecessary. An irregular-shaped thrust front as observed in the field is entirely normal in complex emplacement terranes and does not necessarily imply rotation of individual parts.

Petrographic and heavy-mineral data

Highly quartz-rich sandstone assemblages, such as the Numidian Flysch, are notoriously difficult to work with from a provenance perspective but, conversely, are likely to form excellent reservoirs in the subsurface. The heavy-mineral assemblage has a high proportion of ziron–rutile–tourmaline (a high ZRT index). Both these characteristics at first sight point towards a very mature sandstone provenance, perhaps involving several cycles of erosion and deposition – the ancient African craton, therefore, seemed the perfect match to many early workers. However, more careful scrutiny revealed a significant proportion of polycrystalline strained quartz grains, together with a suite of accessory heavy minerals all indicative of a medium–high grade metamorphic source. Furthermore, around 80% of zircon grains were relatively large, euhedral, prismatic crystals. None of these facets is conducive to an origin through poly-cycling. We freely admit that the evidence is not, however, unequivocal.

Zircon geochronology

The arguments put forward by Thomas *et al.* (2010a) focus almost entirely on the zircon dates we obtained and their comparison with others from the literature. Our dates of 500–550 Ma for the Numidian Flysch from Tunisia and Sicily are consistent with metamorphic ages found in *both* European and African basement blocks – this much we accept. We then argue that the collective additional evidence favours a European provenance, whereas Thomas *et al.* (2010a) favour an African source and then attempt to variously explain away the converse data.

Summary

We are very pleased to see that the Numidian Flysch debate is open. The best way forward will be to gather much additional evidence from many more *new* samples across the length and breadth of the Numidian Flysch succession as well as from potential source regions in Europe and Africa. Both zircon geochronology and zircon morphology are likely to yield important results for the provenance debate. There is much further work still to be carried out on Numidian Flysch sedimentology, part of which is nearly completed for Tunisia (Stow *et al.*, 2009; Riahi, 2010b). As far as we are aware, much more is still open for study across northern Africa, but we should welcome correspondence from any others already engaged in such studies. Furthermore, in our view, the Numidian Flysch was most likely to have been deposited in a series of separate and partly separated basins along the length of the orogenic belt. Distinguishing these basins is an equally important task with considerable significance for hydrocarbon prospects.

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