

Reply to “Comment on Eoalpine (Cretaceous) evolution of the Oman Tethyan continental margin: insights from a structural field study in Jabal Akhdar (Oman Mountains) by J.P. Breton et al.” (GeoArabia, 2004, v. 9, no. 2, p. 41-58) by D.R. Gray and R.T. Gregory (GeoArabia, 2004, v. 9, no. 4, p. 143-147)

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In their comments on our paper (Breton et al., 2004), Gray and Gregory (2004) provided constructive remarks and new information regarding the geodynamic model of the Oman Tethyan margin. We thank them for their interest in our paper and reply to their comments. The new information provided by Gray and Gregory (2004) only concerns the As Sifah subwindow, the lower unit of the lower slab (see Note below). This information does not pertain to the ocean-directed subduction that started in early Turonian and involved the autochthon represented by the Jabal Akhdar and Saih Hatat windows. Because of tectonic continuity between the internal and external zones of Saih Hatat and Al Jabal Al Akhdar, the Turonian subduction involved the upper slab as a single tectonic unit. In Breton et al. (2004), we explained the arguments that demonstrate this fact, which was previously established by several authors (Le Métour, 1988; El-Shazly and Coleman, 1990; Le Métour et al., 1990, 1995; Rabu et al., 1993; Wendt et al., 1993; Miller, 1998; Miller et al., 1998, 1999, 2002). Breton et al. (2004) added the new interpretation that the Muti Formation facies is a typical intra-continental wildflysch.

Gray and Gregory (2004) argue that the lower slab, separated from the upper slab by a regional ductile shear-zone, is characterised by: (1) a specific stratigraphic history (with Carboniferous sediments); (2) a distinct tectonic and metamorphic history (subduction below the Arabian Plate that started at 130 Ma); and (3) an exotic paleogeographic setting, away from the plate margin. Our geodynamic interpretation of the evolution of the northern Oman margin during the Late Cretaceous attempted to incorporate all the known data in a simple geodynamical model. We are aware of its uncertainties and are prepared to modify it to account for any new robust information. In our opinion the new datings of Gray and Gregory are not reliable and require a complex geodynamic model, which does not fit with the well-documented regional geology of the region. The following points briefly explain our reasons for this conclusion.

Age of the Protolithe of the Lower Slab

Gray et al. (paper in preparation provided by D. Gray) do not consider the possibility for the protolithe of the meta-tuffite to be of volcano-sedimentary origin. In such a case the analysed zircons could be detrital, and therefore older than the host-rock.

All the $\delta^{13}\text{C}$ values curves show positive values for Carboniferous and Permian (Grossman, 1994; Ekart et al., 1999; Hayes et al., 1999; Prokoph and Veizer 1999; Scholle 1995). The closest negative values before and after this period occur in Devonian and Triassic, which contradicts the age provided by the zircons. In the high-grade metamorphic context of the lower slab (blueschist to eclogite facies), the negative values obtained from calcschist samples (Gray et al., in preparation), may not represent primary signatures but rather the result of secondary decarbonation reactions in the presence of siliciclastic components (Kaufman and Knoll, 1995; Sharp et al., 1995). These reactions start from the greenschist facies and produce very light carbonate in the system.

Note: Gray et al. (2004) use the term “upper plate” and “lower plate” for the two tectonic units that are separated by a regional ductile shear-zone identified in the internal zone of Saih Hatat (Miller, 1998; Miller et al., 1998, 1999, 2002). To avoid confusion with the main tectonic plates (in particular with the use of upper plate and lower plate in the asymmetric rifting model of Wernicke, 1985), we prefer to use “upper slab” and “lower slab”. The term “slab” indicates the smaller scale of these units in comparison to “plate”.

Timing of Peak Eclogite Facies Metamorphism

The U–Pb SHRIMP dating method on zircon (absolute punctual analyses interpreted on the Concordia diagram) is in principle considered a suitable dating method. The resulting ages often converge with stratigraphic data for non-metamorphic volcanites, or refine metamorphism ages given by indirect information over a wider time bracket.

This is not the same for the Sm–Nd method on garnets, which is an isochron approach with uncertainties and concerns regarding: (a) chemical and isotopic equilibrium on rocks partially or totally reworked, (b) cooling conditions, (c) hydrothermal influence, and (d) contamination. In some instances the age-dating results, based on this method, may be completely erratic. When comparing U–Pb ages and Sm–Nd ages of Alpine and Himalayan eclogites (Luais et al., 2001), Alpine ophiolites (Costa and Caby, 2001) and Granites of Corsica (Poitrasson et al., 1998), it appears that the Sm–Nd ages are the most questionable and have the highest geological interpretation uncertainty. This seems to also be the case for the As Sifah eclogite, for which an U–Pb age of 82 Ma is determined (Gray et al., 2004). This is slightly younger than the Santonian age of the top of the subducted Muti Formation and close to the 80 Ma dating of the metamorphic peak in the upper slab (El-Shazly and Lanphere, 1992) that seems to represent the end of the subduction.

The mono-phased growth of a single generation of zircons suggests for us that the metamorphic peak was reached about 10 million years after subduction had started and was followed by fast exhumation (cooling and pressure decrease). If the zircon age represents a retrograde step, zircons should show zoning with a heart of older age representing the metamorphic peak. Gray et al. (2004) discuss the interpretation of the Sm–Nd 110, 109 ± 15 Ma age and review the known problems related to this method, such as (i) closure of garnet Sm–Nd system, (ii) contamination by inclusions, (iii) equilibrium of components, and (iv) decay constant. Nevertheless they conclude the suitability of this age and use it to date the metamorphic peak of eclogite.

Based on similar examples found in the literature, we estimate that the Sm–Nd method lacks robustness and the 110, 109 ± 15 Ma age attributed to the metamorphic peak of the As Sifah eclogites is not meaningful. Therefore, the hypothesis of a subduction that started at 130 Ma is not realistic, as we will show below.

Possible Exotic Nature of the Lower Slab

Even if the age of the outcropping sediments of the lower slab is Late Carboniferous, it doesn't imply that the lower slab is exotic and was originally an out-of-the-margin microplate. In fact, the wedge-shaped erosion of the autochthon B occurring at the Cenomanian–Turonian boundary and reaching the Triassic Mahil Formation at the latitude of Muscat, may have completely removed the Permian Saiq Formation northeast of Muscat and exhumed an hypothetical Carboniferous graben located within the continental plate margin.

In addition, if the lower slab had been originally separated from the upper slab by an oceanic crust (which is implied, if its origin is outside of margin), the shear-zone presently marking the tectonic superposition contact should be a major suture lined by remnants of oceanic lithosphere. This suture should be overlain by crystalline basement of the upper slab. However this is contrary to the field observations which indicate that the ductile shear-zone juxtaposes directly the two covers and cuts down to the upper slab sequence towards the southwest. To the northeast, the upper slab can then wedge with a tip located at a maximal distance of about ten kilometres northeast of Muscat. The shear zone seems to be only a cutting-down additive under-thrust through the continental margin, with only about several tens of kilometres of displacement (Breton et al., 2004; Figures 8d and 8e).

Hypothesis of a Subduction Initiated in Tithonian-Berriasian

During the Tithonian–Berriasian times the majolica facies covered the whole northeastern part of the Oman continental platform (Rayda Formation), and the distal platforms of the Hawasina Basin (Le Métour et al., 1995). This facies is widespread through the Tethys region from Cuba, the Cap-Verde

Islands, the Alpine-Mediterranean Tethys to Indonesia (Bernoulli and Jenkins 1974; Bosellini and Winterer 1975; Le Nindre et al., 2003). Thus this facies is not related to a specific evolution of the Oman margin. It is coeval with a general progressive deepening of the basin to a medium depth without terrigenous sediment supply, which could have been due to an eustatic sea-level rise (Rousseau et al., 2005). In any case, this facies does not have the character of a back-subduction flexural basin. The east-west paleogeographic evolution of the Jurassic facies (Sahtan Group) from western Al Jabal Al Akhdar to eastern Saih Hatat, may be related to the rifting that led to the opening of the Owen oceanic basin to the east of Oman (Loosveld et al., 1996). The majolica facies could be the consequence of the thermal subsidence of the passive continental margin.

A subduction that lasted between about 140 and 110 Ma (estimated peak of the high-pressure/low-temperature metamorphism) followed by an exhumation that started at 80 Ma, highlights the difficulty in maintaining a high-pressure/low-temperature assemblage during 20–30 million years without thermal relaxation. Gray et al. (in preparation) invoke the requirement for a "descending cool footwall" during this period. With this hypothesis, four distinct subductions are necessary to account for all the phenomena:

- (1) a continental verging subduction starting at about 140 Ma and ending at 110 Ma (lower slab);
- (2) a continental verging subduction also starting at about 140 Ma or thereafter and lasting up to 80 Ma (necessary for cooling footwall);
- (3) the verging southeast intraoceanic subduction, starting at about 100 Ma and becoming obduction, ending at 80 Ma (Samail Nappe); and
- (4) the NE-verging intracontinental subduction, starting at 93 Ma and ending at about 80 Ma (upper slab).

Such a system of subduction events seems unnecessarily complex when compared with the sequential cross-sections of Breton et al. (2004, Figure 8).

Western Lateral Extension of Intracontinental Subduction

As correctly noted by Gray and Gregory, we were not sufficiently specific in interpreting the lateral evolution of the western part of the intracontinental subduction. Following our interpretation, the rapid "dying-out" west of the Saih Hatat dome involves the lower slab block only. This is because its impingement would have triggered the crustal over-thickening responsible of the Saih Hatat doming at the end of the exhumation. It is clear that the subducted area of the upper slab extended westward at least to the western limit of the Hawasina Window, and perhaps up to the inferred southward extension of the Dibba transform.

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