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Discussion on subsidence history of the north Indian continental margin, Zanskar–Ladakh Himalaya, NW India

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E. Garzanti, D. Sciunnach & M. Gaetani write: In their recent paper, Corfield *et al*. (2005) attempted a subsidence analysis of the northwestern Tethys Himalaya stratigraphic succession, and discussed specifically the implications for the obduction of a section of oceanic lithosphere (Spontang Ophiolite) on top of the Indian passive continental margin (Zanskar Shelf).

The controversy. The emplacement age of the Spontang Ophiolite represents a crucial problem in Himalayan geology, which has been lively debated for two decades (e.g., Searle 1986; Kelemen *et al.* 1988; Garzanti *et al*. 1987; Guillot *et al*. 2003). In a series of papers, Mike Searle and co-workers have long proposed and supported the idea that the Spontang Ophiolite was obducted in the Late Cretaceous, making implicit or explicit correlation with the well-studied Semail Ophiolite of Oman (e.g, Searle 1983; 1986; Pedersen *et al*. 2001; Corfield *et al*. 2001, 2005).

Semail and Spontang, however, are two very different ophiolite complexes. The Semail crust has a supra-subduction geochemical signature and was generated in the mid-Cretaceous (Searle & Cox 1999). Instead, the Spontang basalts have a MORB-like signature and were generated in the mid-Jurassic (Pedersen *et al*. 2001), similar rather to the other Oman ophiolite exposed on Masirah Island (Gnos *et al*. 1997). The analogy with the Semail Ophiolite obduction, associated with Late Cretaceous nappe stacking and high-pressure metamorphism of the underthrusted Arabian margin (Searle & Cox 1999), led Searle (2001) to reject the geochronological evidence for the Eocene age of high-pressure metamorphism of Indian-margin rocks (Kaghan and Tso–Morari eclogites; Tonarini *et al*. 1993; De Sigoyer *et al*. 2000).

Because of the Eocene age of the eclogites, and of the fact that the Spontang Ophiolite lies tectonically on top of Indian margin sediments as young as the early Eocene and displaying upward-increasing very low-grade metamorphism of Eocene age (Garzanti *et al*. 1987; Garzanti & Brignoli 1989, fig. 8; Bonhomme & Garzanti 1991; Guillot *et al*. 2003), we favour instead Eocene emplacement of the Spontang Ophiolite during attempted subduction of the distal Indian margin.

The discussion. Aim of the present discussion is to dispute that the available stratigraphic evidence of the Zanskar Tethys Himalaya may be used in support of a Late Cretaceous obduction event. The likelihood that the conclusions of Corfield *et al*. (2005) are largely based on artefacts clearly results from close inspection of their figures 4, 5, and 6. Here uplift of the inner margin is drawn at Late Cretacous 'Chikkim times', whereas subsidence increase of the outer margin is drawn at latest Cretaceous 'Kangi-La times'. But, in the proposed syn-obduction model, flexural uplift of the inner margin cannot precede flexural subsidence of the outer margin under the load of the ophiolite!

Corfield *et al*. (2005) duly considered some (e.g., decompaction, sea-level variations), but by no means all, of the numerous problems that can generate inaccuracies in the reconstruction of subsidence curves. Besides discrepancies between different time-scales (e.g., Haq *et al*. 1988 versus Gradstein *et al*. 2004), these include largely undetermined depositional depth of pelagic deposits and potentially large errors in evaluating stratigraphic thickness of strongly deformed units.

The inner margin succession (Zangla section of Corfield et al. 2005). We studied in detail the sedimentary succession of the inner Zanskar margin both in its proximal parts exposed in the Zangla tectonic unit and in its relatively distal parts exposed in the Zumlung tectonic unit. Stratigraphic thicknesses and depositional environments are well constrained for various intervals of the Giumal Group (Garzanti 1991, figs 7 and 8; Garzanti 1993, tables 1 and 2), where however chronostratigraphic calibration is poor because of scarce microfauna. Conversely, excellent biostratigraphic calibration is available for the overlying Chikkim and Fatu La Formations (Premoli Silva *et al*. 1991, fig. 20), but palaeowater depths can only be hypothesized.

These sources of information, if duly considered, would have allowed Corfield *et al*. (2005) to see that the Late Cretaceous uplift they inferred for the inner Indian margin is likely to be an artefact caused by overestimated depositional depths of Upper Cretaceous strata (Fig. 1; Premoli Silva *et al*. 1991, p. 551).

The outer margin succession (Yulchung section of Corfield et al. 2005). Depositional depths and stratigraphic thicknesses are much less precisely known and often undetermined for outer-margin sections, which were deposited in distal offshore to pelagic settings and underwent more intense tectonic deformation. Cleavage and transposed bedding, widespread in the Yulchung area and farther north in the Shillakong tectonic unit, prevented us to find sections suitable for measurement in the field. Specifically in the Yulchung area, a major décollement horizon separates the tightly folded Albian–Campanian succession from the overlying Tertiary units, which are characterized by a quite distinct style of fold deformation (e.g., Corfield *et al*. 2005, fig. 3). The thickness range of 900–1100 m attributed to distal equivalents of the Kangi-La Formation in the Yulchung section (Kelemen & Sonnenfeld 1983; Corfield *et al*. 2005, table 1), rather than the accurate measure of a continuous stratigraphic section, is a 'guestimate' (greatly exaggerated with respect to the >50 m ascribed to the equivalent Goma Shale by Gaetani & Garzanti 1991, fig. 3) across a major tectonic boundary from an area of multiphase tectonic deformation.

Moreover, no information is available for palaeowater depth of the entire Upper Cretaceous outer-margin succession. Therefore, the sharp inflection of the subsidence curve reconstructed for the Yulchung section and ascribed to flexural loading of the obducting Spontang Ophiolite by Corfield *et al*. (2005) is likely to be an artefact caused principally by overestimated stratigraphic thickness of the Kangi-La Formation.

The conclusion. We conclude that imprecise information on palaeowater depth in the crucial Turonian–Campanian interval

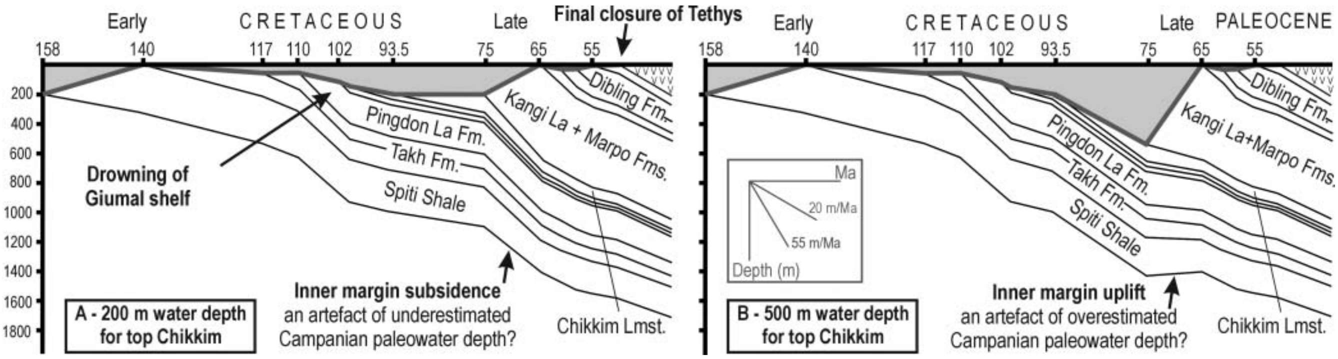

Fig. 1. Alternative subsidence curves for the inner Zanskar margin (Pingdon La–Dibling composite section). Either accelerated subsidence or tectonic uplift is inferred if palaeodepths of 200 m (**a**) versus 500 m (**b**) are assumed for the top of the Chikkim Limestone. More accurate knowledge of depositional depths are needed to constrain the Upper Cretaceous curve (Premoli Silva *et al.* 1991, p. 551). The only undisputable drowning event was recorded by the Zanskar passive margin at latest Albian times. Chronostratigraphic scale after Gradstein *et al*. (2004). Stratigraphic data after Garzanti (1991, 1993) and Premoli Silva *et al.* (1991). Standard decompaction techniques after Allen & Allen (1990). Surface porosity, grain density, and porosity/depth coefficient after Watts & Ryan (1976) and P. Favre (pers. comm 1993).

and on stratigraphic thickness of intensely deformed outer-margin successions invalidate the conclusions by Corfield *et al*. (2005). Not a single piece of evidence from the stratigraphic record of the Zanskar Range indicates or even hints that the Spontang Ophiolite was emplaced onto the Indian margin during the Late Cretaceous.

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R. I. Corfield, A. B. Watts & M. P. Searle reply: We thank Garzanti *et al.* for their comments on our paper (Corfield *et al*. 2005). The fact that the controversy over whether the obduction of the Spontang ophiolite onto the northern continental margin of India occurred during the late Cretaceous–early Palaeocene (Searle 1983, 1986; Corfield *et al*. 2001, 2005) or post-Eocene (Colchen *et al*. 1986; Garzanti *et al*. 1987) is still ongoing, attests to the many complicated geological factors involved in the tectonic interpretation of the region. We welcome therefore this opportunity to explain our reasons for favouring the former over the latter explanation for the timing of ophiolite emplacement.

Garzanti *et al.* raise five main points that we will discuss consecutively below.

Correlation of Spontang Ophiolite with Oman Ophiolite. Despite many similarities between the Spontang ophiolite in Ladakh and the Semail ophiolite in Oman, we did not state that the two are exactly the same. The Semail ophiolite in Oman is one of the few examples of an extremely well-preserved Tethyan ophiolite obducted onto a passive continental margin prior to any continent–continent collision, so we do use Oman as a possible analogy for the pre-continental collision setting of the Himalayan ophiolites. U–Pb dating of the ophiolite crustal sequence, the amphibolite metamorphic sole and the eclogites from Oman has enabled a precise chronology of ophiolite formation (95 Ma) and emplacement (spanning 25–20 million years from 95 to 75 Ma; Searle & Cox 1999, 2002; Warren *et al*. 2003; Searle *et al*. 2004). However our detailed studies of the Spontang ophiolite (Corfield & Searle 2000; Corfield *et al*. 2001), together with our U–Pb dating of the Spontang ophiolite gabbros (177 ± 1 Ma) and the overlying andesitic arc (88 ± 5 Ma; Pedersen *et al*. 2001) shows that the subduction-arc complex was initiated during the late Cretaceous some 80 Ma after formation of the MORB ophiolite crustal sequence.

Relationship between ophiolite emplacement and UHP metamorphism. We did not 'reject the geochronological evidence for Eocene age of high-pressure metamorphism of Indian margin rocks in the northern leading edge of the Indian continental crust (Kaghan and Tso Morari eclogites)'. Rather, Searle (2001, p.191) proposed that the 'eclogite facies metamorphism may have occurred before the India–Asia collision and had nothing to do with Himalayan collisional (kyanite, sillimanite grade) metamorphism'. This interpretation is now further supported by recent precise U–Pb zircon and allanite ages from both the Kaghan eclogites in Pakistan (46.5 Ma; Gough 2002) and the Tso Morari eclogites in Ladakh (53.3 Ma; Leech *et al*. 2005). The eclogites beneath the Semail ophiolite in Oman occur in an identical structural setting to the west Himalayan eclogites, and we used Oman as an analogy for the setting of early Eocene UHP metamorphism immediately prior to the India–Asia collision.

The India–Asia collision can be defined in a number of ways. Our preferred age of collision is the timing of the ending of marine sedimentation along the Indus suture zone and along the northern margin of the Indian plate (Rowley 1996, 1998; Searle *et al.* 1997). In Ladakh and Zanskar, the age of final marine sedimentation is 50–49 Ma (P7–8 planktonic foraminifer zone corresponding to Ypresian stage of the early Eocene). This is 3 million years after the age of peak coesite eclogite metamorphism at Tso Morari, along the leading edge of the Indian continental crust.

Structural relationships between the Spontang ophiolite and Palaeogene sediments. Most geologists mapping in Ladakh are agreed that the Spontang ophiolite rests on a thrust contact above late Palaeocene–early Eocene foraminiferal limestones. This thrust is not the original obduction thrust however, but is a much later, post-Eocene out-of-sequence thrust, a timing that is common to all the thrusts along the northern margin of the Indian plate from the Spontang ophiolite north to the Indus suture zone. This out-of-sequence geometry can be directly mapped in the Marling Valley, west of the Singe La, where the thrust plane cuts through and truncates the Palaeocene stratigraphy (Corfield *et al*. 1999). Structural cross-sections have to be restored in reverse time sequence, and we point readers to the detailed structural map, cross-sections and restored sections in Corfield & Searle (2000). We do not wish to repeat all the structural arguments here, but simply point out that the thrust that places ophiolite over Eocene limestones cannot be the original obduction thrust, as postulated by Garzanti *et al.*

In summary, the stratigraphic, structural and U–Pb geochronological evidence all points to the following evolution:

177 Ma Toarcian (early Jurassic): MORB Spontang ophiolite formation

88 Ma (Coniacian, late Cretaceous): subduction beneath the Spontang ophiolite generated an andesitic arc above the MORB pillow lavas

88–65 Ma (Maastrichtian, late Cretaceous): obduction of the Spontang ophiolite onto the north Indian continental margin complete

53 Ma (Ypresian, early Eocene): UHP metamorphism at 80–100 km depth along the leading edge of Indian continental crust (Tso Morari coesite eclogites)

49 Ma (late Ypresian, early–mid Eocene): closing of Tethys, ending of marine sedimentation, initiation of continent–continent collision

32–20 Ma (Oligocene–early Miocene): timing of high-grade kyanite and sillimanite Barrovian metamorphism along the high Himalaya in Zanskar (Searle *et al.* 1992; Noble & Searle 1995; Vance & Harris 1999).

Stratigraphic thickness of the Kangi-La formation. Garzanti *et al.* suggest that our thickness estimate for the Kangi-La formation in the Yulchung section is a ‘guestimate’, pointing out that the high degree of deformation in the area preclude accurate measurement of the stratigraphic thickness. This is an issue that has long clouded the discussion on the timing of obduction with estimates for the thickness of the Kangi-La formation varying widely in the literature from 400 m (Gaetani *et al*. 1980) to 1000 m (Fuchs 1977) for the type locality alone. Garzanti *et al.* are, however, correct to point out the importance of this thickness to the backstrip subsidence and uplift curves. The nature of deformation in the Kangi-La formation is chaotic with numerous shear zones and small-scale folds in addition to the larger-scale fold and thrust structures. Since it is impossible to follow any internal marker horizons even a small distance through the complex structures the only valid method for estimating the thickness of such a highly deformed unit is by the area balancing of cross-sections. The construction and restoration of balanced cross-sections can only be carried out with a detailed mapping of the regional structure. The work carried out by Corfield & Searle (2000) has allowed us to area balance numerous sections and provides a strong foundation for our thickness estimate of 900 to 1100 m for the Kangi La formation in the Yulchung section.

Subsidence and uplift history and ophiolite loading. Garzanti *et al.* suggest that our backstrip results show differing timings of uplift at Zangla during ‘Chikkim/Fatu La’ times and subsidence at Yulchung during ‘Kanga-La’ times and therefore that they are incompatible with a late Cretaceous ophiolite loading model.

We believe, however, that Garzanti *et al.* have over-interpreted our backstrip results. As we have pointed out on a number of occasions in previous (Watts & Ryan 1976) and current (Corfield *et al*. 2005) work, backstrip curves depend critically on the sea-level curve assumed, as well as on other factors, most notably the water depth of deposition. Therefore, it is necessary when interpreting such curves to take into account all the uncertainties in the magnitude of sea-level and water depth of deposition, among other factors.

Figure 5 in Corfield *et al*. (2005) shows that it is the case that backstrip curves based on Watts & Steckler (1979) sea-level suggest uplift at Zangla during Chikkim/Fatu La and subsidence at Yulchung during Kangi-La. This is irrespective of whether the water depth is nearer the shallow or deep end of the range. However, it is also true that if the water depth is deep then Yulchung shows uplift during Chikkim/Fatu La and, significantly, Zangla shows uplift during Kangi-La. These observations are not in conflict with the predictions of the flexural loading model. To the contrary, they suggest a model in which there is uplift at Zangla *and* Yulchung during Chikkim/Fatu La times as both sites ‘ride’ a bulge generated by distal ophiolite loading, followed by a coeval uplift at Zangla and subsidence at Yulchung during Kangi-La time as the centre of mass of the ophiolite load advances. Similar scenarios could be constructed for the Pitman (1978) sea-level curve data.

The backstrip curves based on the Haq *et al*. (1988) sea-level curve and shallow-water depths are interesting because they also show coeval uplift at Zangla and subsidence at Yulchung during Chikkim/Fatu La times. Therefore the Haq *et al*. (1988) curve does not require the earlier distal uplift ‘event’ and is fully compatible with a proximal ophiolite loading model.

We caution, however, that the amplitude of the flexural bulge is small and there might be a delay, due to the viscoelastic response of the lithosphere, between subsidence in the load region and uplift in the bulge region. We accept therefore that uncertainties in sea-level and depth of deposition, together with uncertainties in the time-scales of isostatic adjustment, preclude the confident identification of uplift in backstrip curves as due to a flexural bulge. However, we believe that our conclusion that the region experienced a significant subsidence is robust against all the uncertainties we have discussed above, as well stratigraphic thickness. The subsidence was initiated during either Chikkum/Fatu (Haq *et al.* sea-level) or Kangi-La (Watts & Steckler and Pitman sea-level) times and is therefore entirely compatible with a late Cretaceous emplacement of the Spontang ophiolite.

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E. Garzanti, Dipartimento di Scienze Geologiche e Geotecnologie, Università di Milano-Bicocca, Piazza della Scienza 4, 20126 Milano, Italy (e-mail: eduardo.garzanti@unimib.it)

D. Sciunnach, Struttura Sistema Informativo Territoriale, Regione Lombardia, Via Sassetti 32/2, 20124 Milano, Italy

M. Gaetani, Dipartimento di Scienze della Terra Ardito Desio, Università di Milano, Via Mangiagalli 34, 20133 Milano, Italy

R. I. Corfield, Department of Earth Sciences, Oxford University, Parks Road, Oxford, OX1 3PR, UK and Present address: BP Exploration, Farburn Industrial Estate, Dyce, Aberdeen, AB21 7PB, UK

A. B. Watts, Department of Earth Sciences, Oxford University, Parks Road, Oxford, OX1 3PR, UK

M. P. Searle, Department of Earth Sciences, Oxford University, Parks Road, Oxford, OX1 3PR, UK

Scientific editing by Rob Strachan