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Structural evolution and sequence of thrusting in the High Himalayan, Tibetan-Tethys and Indus Suture zones of Zanskar and Ladakh, Western Himalaya: Discussion

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M. P. Searle's recent paper in the *Journal of Structural Geology* (Searle 1986) included a major departure from published structural interpretations of the Ladakh Himalaya. The geologic history of Ladakh is a vital key to understanding the timing and sequence of events during the Himalayan orogeny. Ophiolitic rocks and island arc volcanics along the Indus Suture zone (Frank *et al.* 1977, and many others) constitute remnants of a broad oceanic basin, formerly north of the Indian craton. The closure of this basin, and the 'collision' of the Indian continental margin with a subduction-related magmatic arc, marked an important event early in the orogeny. It is important to reconstruct the sequence of other major thrust events, for instance the emplacement of the ophiolitic Spongtang Klippe southward over platform sediments of the northern Indian continental margin, in relation to the time of closure. In Ladakh, closure along the Indus Suture zone is thought to have occurred about 55 Ma (Klootwijk *et al.* 1979).

Searle's more general postulates regarding collisional tectonics are difficult to test, and thus are beyond the scope of our criticism. The most important regional hypothesis advanced in his paper is that the ophiolitic Spongtang Klippe, about 30 km south of the Indus Suture zone, was emplaced between 75 and 60 Ma, prior to deposition of the Paleocene to Lower Eocene Lingshet Limestone. He specifically states that "the Upper Paleocene Lingshet limestones . . . are not in original direct contact with the Spongtang Ophiolite", and shows the two units as spatially separate (about 5 km apart) on his geologic map (Searle 1986, fig. 2). However, observations made by three independent teams show that the basal thrust of the Spongtang Klippe directly overlies, and truncates antiformal hinges in, the Paleocene–Lower Eocene limestone (Fuchs 1982, Kelemen & Sonnenfeld 1983, Colchen & Reuber 1986, Reuber 1986). In addition, Eocene strata have been identified in the melange at the base of the klippe (Colchen *et al.* in press). Thus the final emplacement of the klippe must post-date Lower Eocene sedimentation (at least as young as 55 Ma).

Thrusting of the klippe may have begun substantially earlier than its final emplacement, especially if the possibility of intra-oceanic faulting (Reuber 1986) is considered as part of the emplacement 'event'. There is little data constraining the time at which the klippe was first thrust over the northern Indian passive margin. Searle presents the Maastrichtian Kangi La Formation as a "syn-emplacement 'flysch' deposit" which accompanied thrusting of the Spongtang Klippe. However, the Kangi La Formation is quartz-rich and apparently contains sediments derived only from the passive margin of northern India. The first known sedimentologic evidence for the presence of oceanic basement and arc volcanics in the Indian succession is found in the post-Paleocene Chulung La slates (Garzanti & Gaetani in press).

The relations shown on Searle's map contradict other published maps of the area. It is not clear whether Searle was unaware of this contradiction or whether he disagrees with earlier observations. In the latter case, of course, the reasons for such disagreement should have been stated. The interpretation of Searle's phrase: "*original* direct contact" [emphasis added] is open to question. If it means that the klippe was thrust onto the northern Indian platform earlier than the post-Lower Eocene and later moved along a reactivated thrust fault to its present position, then this should have been explicitly stated and justified.

The relative timing of emplacement of the klippe and deposition of the limestone is of great tectonic significance. Paleocene limestone, equivalent to that beneath the klippe, is reported to overlie the Cretaceous and earliest Tertiary arc volcanics and volcanoclastic rocks of the Indus Suture zone (Wadia 1937, van Haver 1984). It seems likely that the presence of this regionally extensive limestone indicates formation of a shallow, quiescent basin after cessation of plate-scale convergence and closure along the suture. If this is true then final movement of the klippe post-dated closure, whereas Searle (1986) suggests that emplacement of the klippe *pre-dated* closure, and many authors tentatively infer that emplacement was synchronous with closure (e.g. Frank *et al.* 1977). The klippe probably had a polyphase structural history including long-lasting episodes of thrusting (Fuchs 1982, Reuber 1986), but it is beyond the scope of this comment to propose a detailed sequence of events. Any such hypothesis must be rigorously justified by detailed mapping and accurate stratigraphic data.

To summarize, it is beyond doubt that final emplacement of the Spongtang Klippe was post-Lower Eocene, not between 75 and 60 Ma (late Cretaceous to Lower Paleocene) as stated by Searle. Final movement was at least coeval with, and probably post-dated, closure along the Indus Suture zone approximately 55 Ma.

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The crux of the discussion by Kelemen, Reuber and Fuchs relates to the age of obduction of the Spongtang Ophiolite thrust sheet in the Zanskar Range of the NW Indian Himalaya, a topic that has been hotly debated in the recent Himalayan Workshop meetings at Leicester in 1985 and Nancy in 1986. Firstly much confusion in the literature has arisen due to the different interpretations of terminology, notably the terms ophiolite, obduction and emplacement. The *Spongtang Ophiolite* refers solely to the ophiolite *sensu stricto* sequence (i.e. ultramafic mantle sequence, gabbros, cumulates, dykes or sills, pillow lavas) following the Penrose ophiolite definition (Coleman 1977). It does *not* include the various sedimentary (Lamayuru Complex, Goma Formation, etc.) or andesitic volcanic (Dras formation) rocks immediately beneath the ultramafic rocks. *Ophiolite obduction*, a term originally proposed by Coleman (1971), refers to the process of displacing oceanic crust and mantle onto a continental margin. *Emplacement* is generally used synonymously with obduction. If we agree that the ophiolite was oceanic crust and mantle then obduction or emplacement must have been prior to ocean closure (T1). Subsequent (post-collision) deformation involved several phases of complex thrust stacking (T2, T3), and is related to continental collison tectonics, not to earlier subduction–obduction–emplacement tectonics.

The Spongtang Ophiolite is a slab of Tethyan oceanic crust and mantle sequence rocks in which the volcanic component has a dominant MORB-chemistry and the harzburgite–dunite–lherzolite mantle component is over 2 km thick. It was thrust southwards onto the north Indian continental margin from an oceanic site north of the Zanskar Shelf margin. Similar obducted ophiolite slabs which are better constrained and better studied (notably Oman and Western Newfoundland) show that a complex history of thrusting spanning *ca* 20–25 Ma involves hundreds of km of translation (see Searle & Stevens 1984 for review and references). Obduction processes (Dewey 1970, Coleman 1977) begin as intra-oceanic mantle-tapping ductile shear-zones (e.g. Reuber 1986) or thrust faults which are subduction-related (e.g. Searle & Malpas 1980), and generally evolve into thinner-skinned brittle thrust-related structures. Deep level ductile detachment zones with high-temperature plastic flow fabrics become shallower level brittle thrust faults with decreasing depth and increasing time.

The stratigraphy of the Zanskar Shelf sequence has been extensively studied (e.g. Fuchs 1979, 1982, Kelemen & Sonenfeld 1983, Gaetani *et al.* 1983, 1985, etc.) and it is possible to constrain the timing of closure of Tethys along the Indus Suture zone in Ladakh. Palaeomagnetic studies indicate closure at around 55 Ma (Klootwijk *et al.* 1979). Stratigraphic studies indicate closure at around 50 Ma, which is the age of the youngest marine sediments on the Zanskar Shelf–Spanboth Formation shallow marine carbonates of Palaeocene age in Western Zanskar, or Palaeocene–Lower Eocene Lingshet limestones in central Zanskar. Overlying the Spanboth Formation are a sequence of purple and green continental ferruginous slates of early Eocene age (Chulung La Formation). There are *no* marine sediments younger than early Eocene on the Zanskar Shelf or along the Indus Suture zone (van Haver 1984). Continental molasse deposition (Indus Group) dominated the suture zone after this time and closure of Tethys and collision of India with the northern plate can be constrained at *ca* 50 Ma. There are few certainties in Ladakhi geology but one *can* say with certainty that