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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

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Abstract—The timing of motion on major thrusts in the Western Himalaya shows an extremely complex sequence that spans approximately 70 Ma from the latest Cretaceous throughout the Tertiary. Three major phases of thrusting can be distinguished. The earliest phase (T1) is associated with emplacement of Tethyan basin thrust sheets (Lamayuru sediments and Spontang ophiolite) south and south-westwards onto the submerged northern passive margin of India (75–60 Ma). Collision between India and Asia occurred at 50–36 Ma and was followed immediately by the major phase (T2) of crustal shortening involving large-scale south and south-westward directed thrusting of the complete Palaeozoic, Mesozoic and Late Tertiary Tibetan–Tethys zone rocks. Preliminary balanced cross-sections show a minimum shortening of 126 km of these rocks across the Zanskar Range. The late collision phase (T3) involved re-thrusting of the previously stacked pile (breaching or leap-frog thrusting) reversing the earlier stacking order in places, and widespread steepening, overturning and backthrusting along the whole northern margin of the Tibetan–Tethys zone and throughout the Indus suture zone.

INTRODUCTION

THE MAIN mechanism of crustal shortening in supra-crustal rocks is thin-skinned thrust tectonics, typically displayed in foreland fold and thrust belts. In the more internal parts of orogenic belts the basal décollement descends to deeper structural levels, and commonly involves mid-crustal or lower crustal rocks (Boyer & Elliott 1982). In continent-continent collision zones, typified by the Himalayan thrust belt (Fig. 1), thrusts extend down to the base of the crust (Hirn *et al.* 1984a,b). Because of this deep thrusting, and the extreme altitude and deep erosion levels in the resulting mountain belts, lower or mid-crustal thrust processes that can normally be deduced only by seismology and modelling, can be studied in the field. The Himalayas therefore provide a unique playground for testing kinematic models for thrust processes.

Balanced cross-sections are a key tool for interpreting minimum displacements, and have been used to good effect in relatively simple foreland fold and thrust terrains such as the Canadian Rocky Mountains (e.g. Bally *et al.* 1966, Price, 1981), the Moine Thrust Zone, NW Scotland (Elliott & Johnson 1980, Butler 1982, Coward 1984) and the Salt Ranges of Pakistan (Coward & Butler 1985). Geological sections have been successfully balanced (restored) only in regions of 'piggy-back' thrusting, where thrusts propagate successively downwards towards the foreland, and cut up stratigraphic section in the transport direction.

The more internal parts of mountain belts are generally considerably more complex than simple foreland fold and thrust belts. Where 'out-of-sequence' thrusting has occurred, some stratigraphic section may have been removed and the section cannot balance without a certain amount of inference. Thrusts can be shown to be 'out-of-sequence' if they truncate footwall structures such as folds and imbricate thrusts, emplace younger rocks onto older rocks, or eliminate stratigraphic section in the footwall (Searle 1985).

Reversals of the regular stacking order of thrust sheets have been documented in several allochthonous terrains and have been attributed to either "leaky duplexes" (Butler 1983) where imbricate thrusts do not converge into alignment with the roof thrust but actually penetrate up into (breach) the overlying thrust sheet, or 'leap-frog' thrusting. 'Leap-frog' thrusts cut through a previously assembled stack of thrust sheets, and invert the earlier stacking order by putting originally lower and younger thrust sheets over originally higher and older thrust sheets (Searle 1985). Cross-sections must be sequentially restored in reverse time sequence in these terrains.

Because of the altitude and inaccessibility of the Zanskar Himalaya, maps are not yet sufficiently detailed or well defined to allow section restoration without an unacceptably high level of inference. The complexities of the internal geometry of thrust sheets in the Zanskar Mountains are considerably greater than in the simple foreland fold and thrust belt exposed in the Salt Ranges and Siwalik Hills.

This paper attempts to define the main stages of motion on Himalayan thrusts in the Ladakh, Zanskar, Kishtwar and Kulu–Lahoul regions of NW India. Determination of the sequence of thrusting depends on tying in structures to accurate stratigraphy, and mapping out the thrust geometry along two main traverse lines west and east of the Zanskar River gorge (Fig. 2).

GEOLOGY OF THE HIMALAYAN TETHYS

A geological map of Kashmir, Ladakh and Zanskar and the High Himalayan Ranges in the Indian provinces

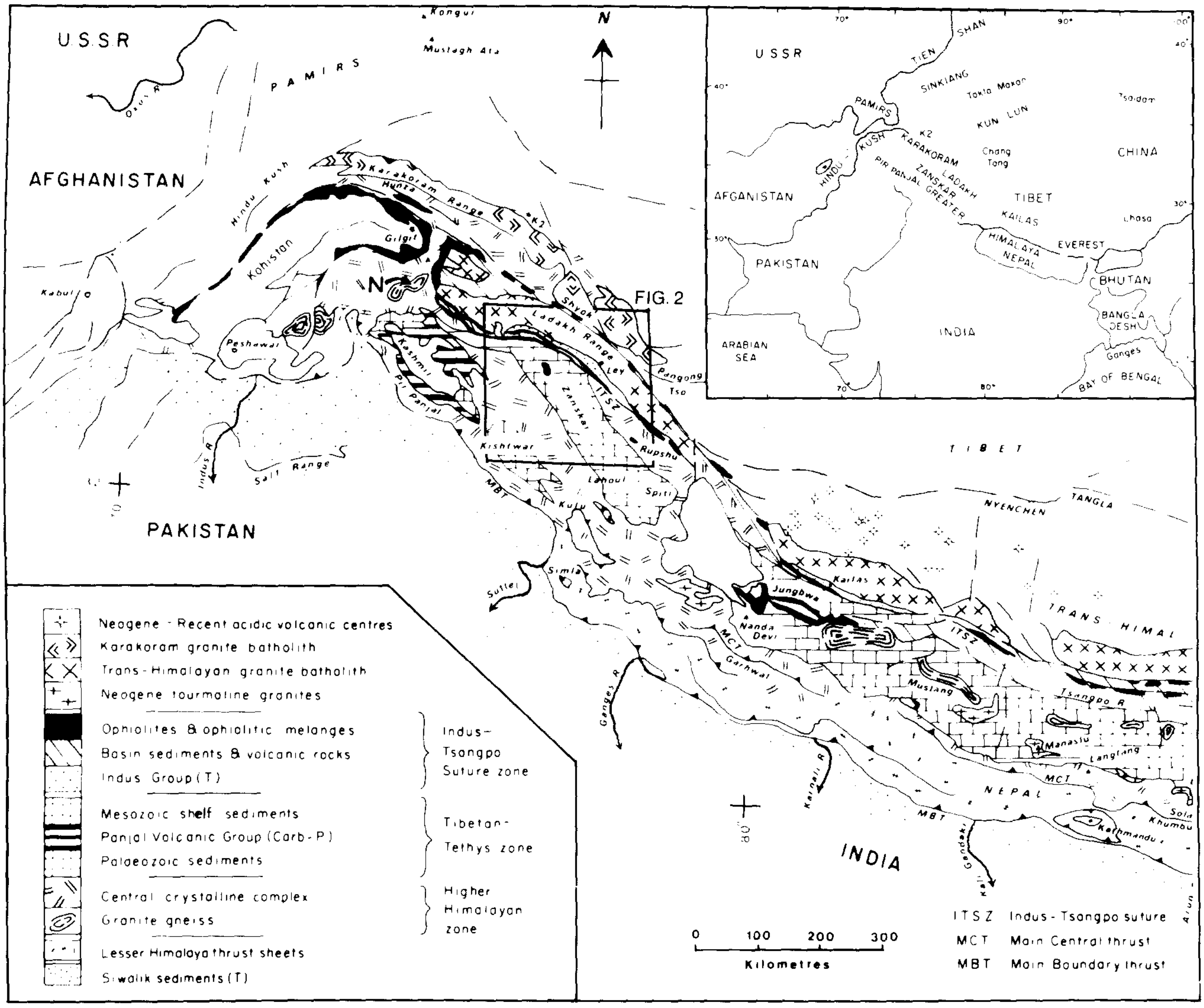

Fig. 1. Geological sketch map of the western Himalaya and Karakoram Mountains. N, Nanga Parbat. Inset map shows the major mountain ranges of Central Asia.

of Kishtwar, Chamba, Kulu and Lahoul is shown in Fig. 2. It is based on three expeditions by the author, following the reconnaisance maps of Gansser (1964), Fuchs (1979) and Srikantia & Razdan (1980). Four tectonic zones are distinguished in the area.

High Himalayan central crystalline complex

This zone comprises Precambrian basement and Palaeozoic–Mesozoic cover rocks, metamorphosed during the climax of Himalayan orogeny during the mid-Tertiary (Frank *et al.* 1977b) and intruded by Miocene leucogranites, adamellites and other S-type granites (Searle & Fryer 1985). Protoliths for the metamorphic rocks are as young as Jurassic (Powell & Conaghan 1973); and unmetamorphosed sediments, possibly as young as Cretaceous, occur in the cores of tightly folded synclines such as the Udaipur–Tandi syncline along the Chenab river, within the central crystalline complex. Metamorphism increases northwards from the Chenab valley to the Zanskar Valley and isograds generally dip north; the metamorphism is therefore inverted (hot side up). Kyanite- and sillimanite-bearing garnet–two mica gneisses and sillimanite–K-feldspar gneisses occur south of the Zanskar Valley (Honegger *et al.* 1982, Searle 1983a). Garnet–muscovite–tourmaline leucogranites intrude the metamorphic rocks and are intimately associated with migmatites, from which they formed by partial anatexis (Searle & Fryer 1986).

Tibetan–Tethys zone

The Zanskar Range is comprised of Cambrian to Eocene sediments representing the shelf and shelf-edge facies along the northern continental margin of the Indian plate (Fig. 3). The Phanerozoic sediments are divided into the Palaeozoic Lahoul Supergroup and the Mesozoic Zanskar Supergroup, divided by the Carboniferous–Permian Panjal volcanic group. The Panjal volcanics comprise continental tholeiites and alkali basalts with marine tholeiitic pillow basalts that record the rifting of Tethys and the breakup of Gondwana.

The Mesozoic Zanskar sediments are dominantly of shelf carbonate facies (Gansser 1964, Gupta & Kumar

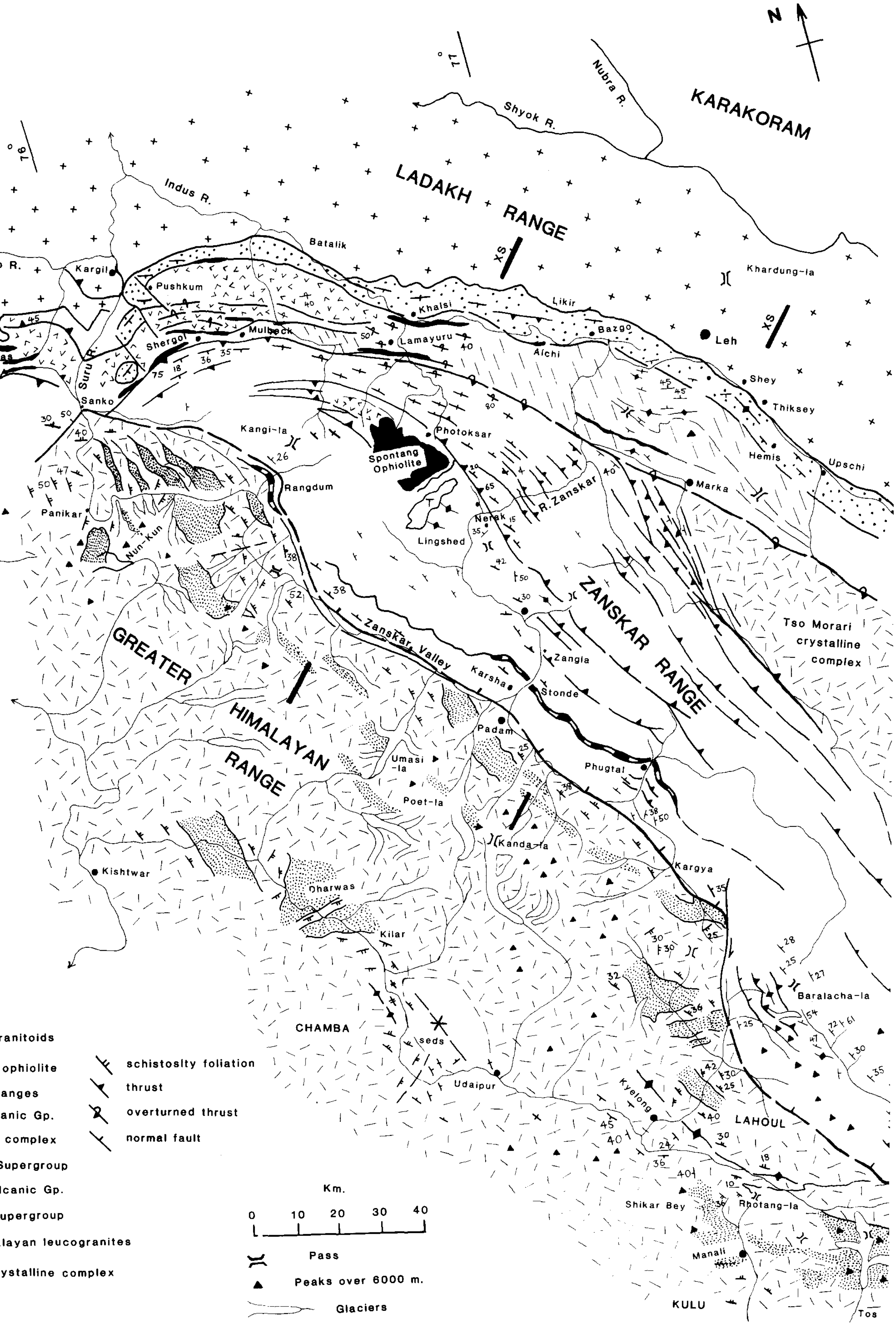

Fig. 2. Geological map of Ladakh and Zanskar. I.S.Z., Indus suture zone.

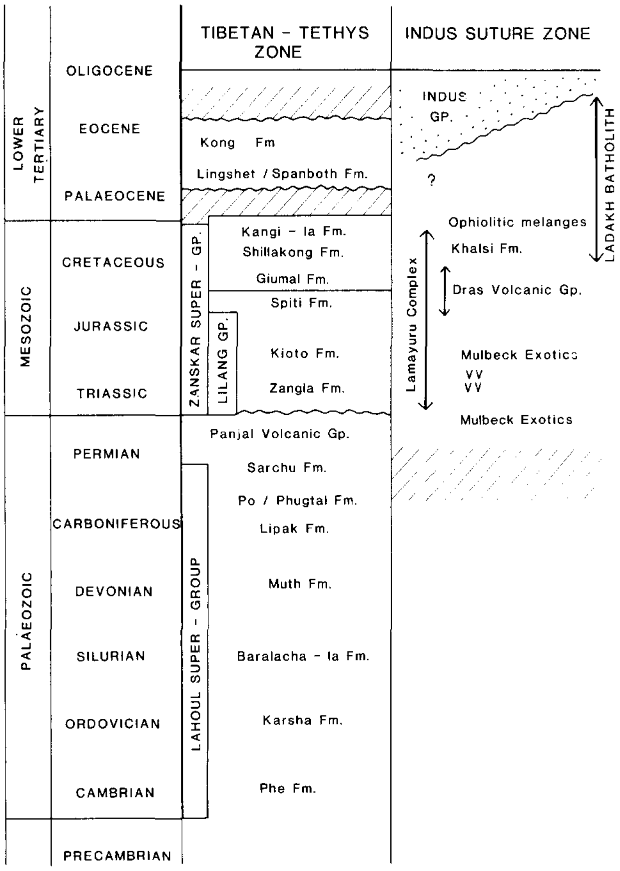

Fig. 3. Stratigraphy of the Tibetan–Tethys and Indus suture zones of the north margin of the Indian plate.

1975, Fuchs 1979, 1981, Baud *et al.* 1984). Two distinct marine transgressions or deepening events are recorded with the Upper Jurassic Spiti shales and with the latest Cretaceous Kangi-la flysch (Fig. 4). Gaetani *et al.* (1983) and Mathur & Pant (1983) describe late Palaeocene and Early–Middle Eocene carbonates, and these are the youngest sediments in the Tibetan–Tethys zone.

Indus suture zone

Mesozoic sedimentary rocks in the Indus suture zone in Ladakh (Lamayuru complex) are time equivalent rocks of the Zanskar shelf carbonates, but of a more distal facies and palaeographic position (Fig. 5). The Dras volcanic group comprises a thick andesitic–basaltic island-arc sequence composed of clinopyroxene and hornblende phyric lavas of Jurassic–Cretaceous age (Frank *et al.* 1977a, Honegger *et al.* 1982, Searle 1983a). The oldest rocks in the suture zone appear to be Permian and Triassic exotic limestone blocks, Triassic deep-water sediments and alkali basalts. Thick post-collisional molasse deposits (Indus group) of probable Eocene to Miocene age crop out along the Indus suture zone in Ladakh and along the Tsangpo Valley in Tibet.

Ladakh (Trans-Himalayan) granitoid batholith

This 2000 km long, 30 km wide batholith comprises biotite–hornblende granites, tonalites and granodiorites with minor gabbros and norites, which intrude the Indus suture zone around Kargil and westwards into Pakistan. In central Ladakh the batholith divides the Indus and Skyok (northern) suture zones (Thakur 1981). Radiometric ages of the granites span Albian to Eocene time (Honegger *et al.* 1982, Scharer *et al.* 1984). The Ladakh batholith continues westward as the Kohistan batholith in Pakistan (Coward *et al.* 1982, 1986) and eastwards into Tibet where it is known as the Gangdese batholith (Allegre *et al.* 1984).

The structural evolution of the Ladakh–Zanskar Himalaya can be discussed in a chronological sequence with reference to the time chart (Fig. 4), the palinspastically restored section across the Indian continental margin (Fig. 5), and the two cross-sections across the Zanskar Ranges (Figs. 6 and 7). Three major phases of crustal shortening are described—the pre-collision ophiolite obduction stage (T1), the continental collision stage (T2) and the post-collision stage (T3).

OPHIOLITE EMPLACEMENT STAGE (T1)

The earliest stage of Himalayan thrusting is difficult to deduce because of the extreme overprinting by the subsequent phases of crustal shortening during continental collision. However, by detailed mapping combined with stratigraphic dating it is possible to deduce a sequence of events with time. The Spontang ophiolite klippe approximately 30 km south of Lamayuru in the Zanskar Range (Fig. 2), rests on allochthonous Lamayuru sediments and mélanges similar to those exposed in the suture zone. A cross-section through the Spontang area is shown in Fig. 6. Early thrusts below the ophiolite and underlying Lamayuru slices are truncated by the later steep SW-directed Photoksar thrust. The root zone for the Spontang thrust sheets must be the Indus suture zone (Gansser 1964, 1980), along which relict ophiolitic melanges (e.g. Shergol melange) and one complete ophiolite sequence in eastern Ladakh (the Nidar ophiolite) are now preserved.

The age of obduction of the ophiolite is controversial. Frank *et al.* (1977a), Thakur (1981), Fuchs (1979, 1981) and Baud *et al.* (1984) consider ophiolite emplacement to be post-Eocene. However, the Upper Palaeocene Lingshet limestones and Lower–Middle Eocene Kong Formation that overlie the allochthonous (T1) Lamayuru thrust sheets around the Singe-la area of Zanskar (Fig. 8c & d) are not in original direct contact with the Spontang ophiolite. Ophiolite obduction is usually preceded by a collapse of the passive continental margin creating a rapidly deepening trough which migrates with the peripheral bulge towards the foreland in front of the advancing thrust sheets (Searle & Stevens 1984). Ophiolites are never emplaced directly on top of shallow water carbonates. Searle (1983a,b) proposed a Late Cretaceous–Palaeocene age of emplacement and regarded the Maastrichtian Kanji-la Formation, consisting of more than 1000 m of deep-water shale and olistostromes, as the syn-emplacement 'flysch' deposits

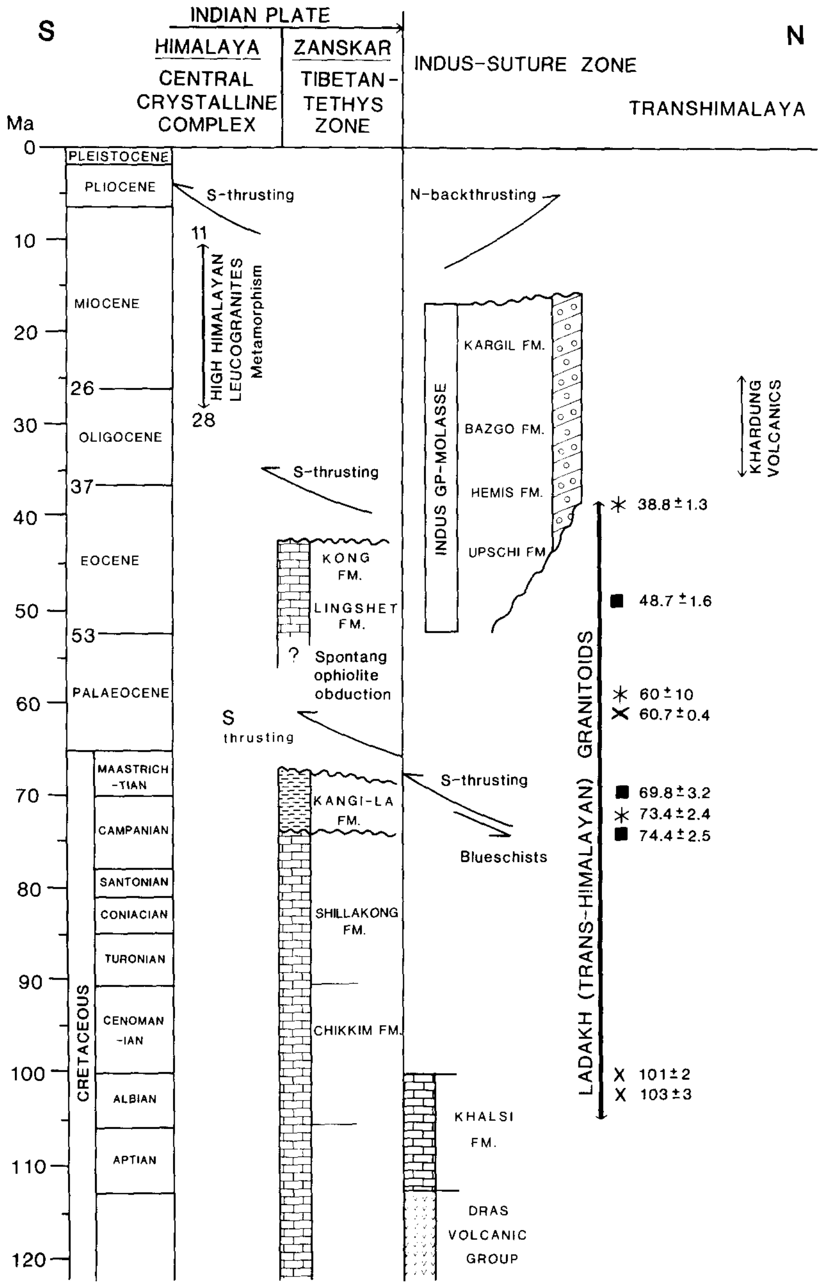

Fig. 4. Revised time chart for the Late Cretaceous and Tertiary rocks of the High Himalaya, Tibetan–Tethys and Indus suture zones and the Ladakh (Trans-Himalayan) batholith in the western Himalaya. Radiometric ages for the Ladakh batholith are from Honegger *et al.* (1982) and Scharer *et al.* (1984). Crosses, U–Pb zircon ages; squares, K–Ar mineral ages; stars, Rb–Sr ages.

accumulating in the foredeep on the Indian plate margin. The late Palaeocene–Eocene Lingshet and Kong Formation limestones would then be regarded as the T1 stage neo-autochthonous cover.

The earliest phase of thrusting is therefore regarded as the late Cretaceous–Palaeocene S- and SW-directed thrusting of Tethyan sediments, volcanics and the Spontang ophiolite onto the depressed northern continental margin of India. In Pakistan, the Main Mantle Thrust (MMT) is a major crustal-scale thrust carrying the Kohistan island arc sequence along the hanging-wall (Tahirkheli & Jan 1979, Bard 1983, Coward *et al.* 1982, 1986). Thrust-bounded wedges of granulites (Jijal complex) and blueschists crop out along the MMT in southern Kohistan (Pakistan).

The granulites of the Jijal complex have a Sm–Nd isochron of 103 Ma (Thirlwall in Coward *et al.* 1986), indicating that they formed prior to collision at the base of the Kohistan arc. The blueschists near Shang-la in Pakistan have a ^{39}Ar/^{40}Ar age of 80 ± 5 Ma (Maluski & Matte 1984). The blueschists in Ladakh and Kohistan indicate that northward subduction beneath, and consequently southward thrusting of the Kohistan arc onto the Indian plate, was active during the late Cretaceous. Eocene sediments overlie the deformed arc sequence in Central Kohistan (Windley *et al.* in review), and are themselves tightly folded and imbricated.

In the southern Tibet (Xixang) section of the Indus–Tsangpo suture zone the Xigase ophiolite was also obducted during the Late Cretaceous–Palaeocene, and

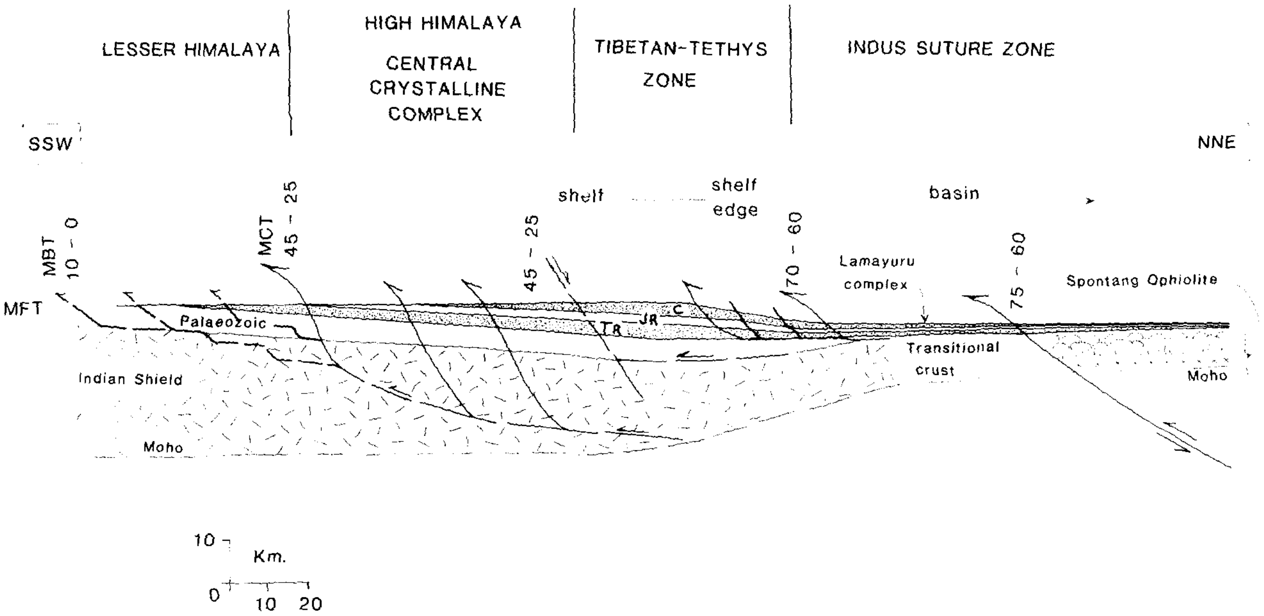

Fig. 5. Palinspastic reconstruction of the northern continental margin of the Indian plate and the Tethyan oceanic margin in the late Cretaceous, prior to thrusting, showing relative paleogeographic positions of the main rock units. Positions of major thrusts are highly schematic. Numbers at tip line give approximate timing (in Ma) of motion. The Tibetan–Tethys and Indus suture zones restore to an absolute minimum of 224 km (see Fig. 7). Length of section is at least 300 km.

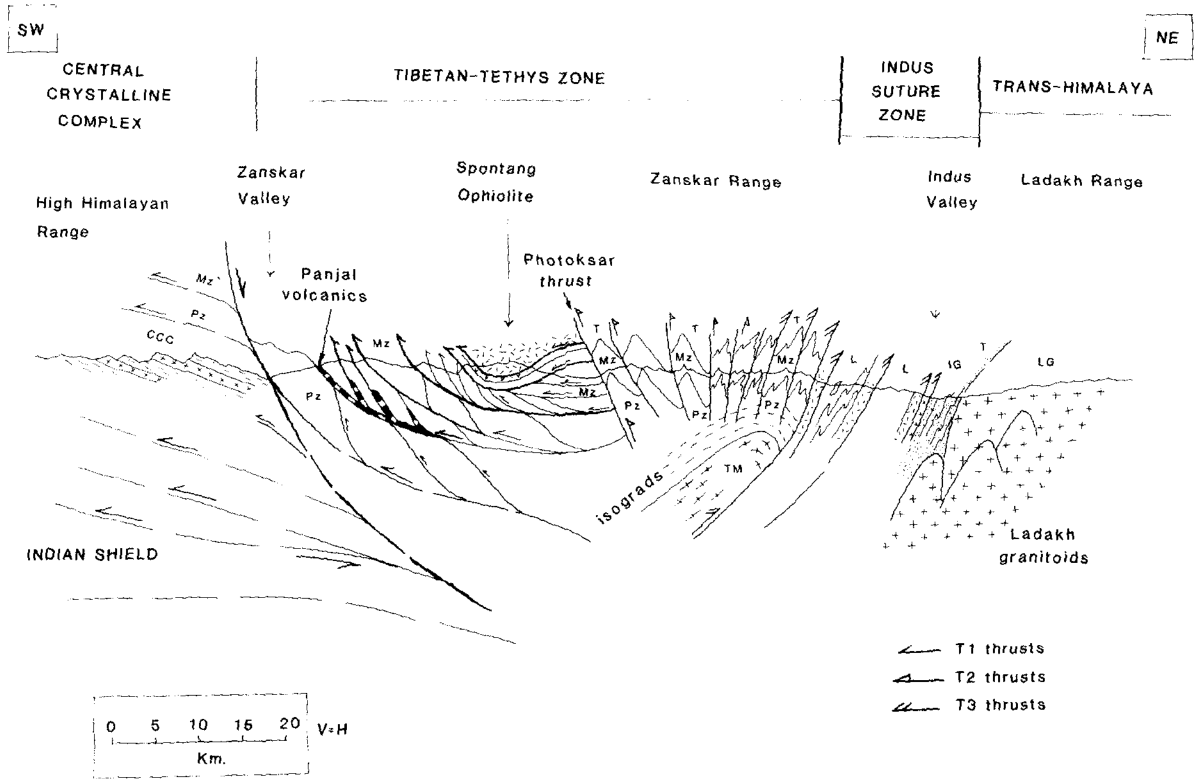

Fig. 6. Structural cross-section across the Zanskar mountains, Spontang ophiolite and Indus suture zone west of the Zanskar River gorge. CCC, Central Crystalline Complex; the Palaeozoic (Pz) and Mesozoic (Mz) sediments are divided by the Permian Panjal volcanic group (striped pattern). IG, Indus Group molasse; L, Lamayuru Complex; LG, Ladakh granitoids; T, Tertiary sediments; TM, Tso Morari crystalline rocks. Stippled pattern, ophiolitic rocks. The Photoksar thrust is the major late stage, leap-frog thrust along the NE margin of the Spontang ophiolite. The Cretaceous–Tertiary boundary restores to an absolute minimum of 122 km from the Photoksar thrust to the Ladakh batholith. The present length being 47 km, the shortening from the Spontang ophiolite to the suture zone is more than 75 km.

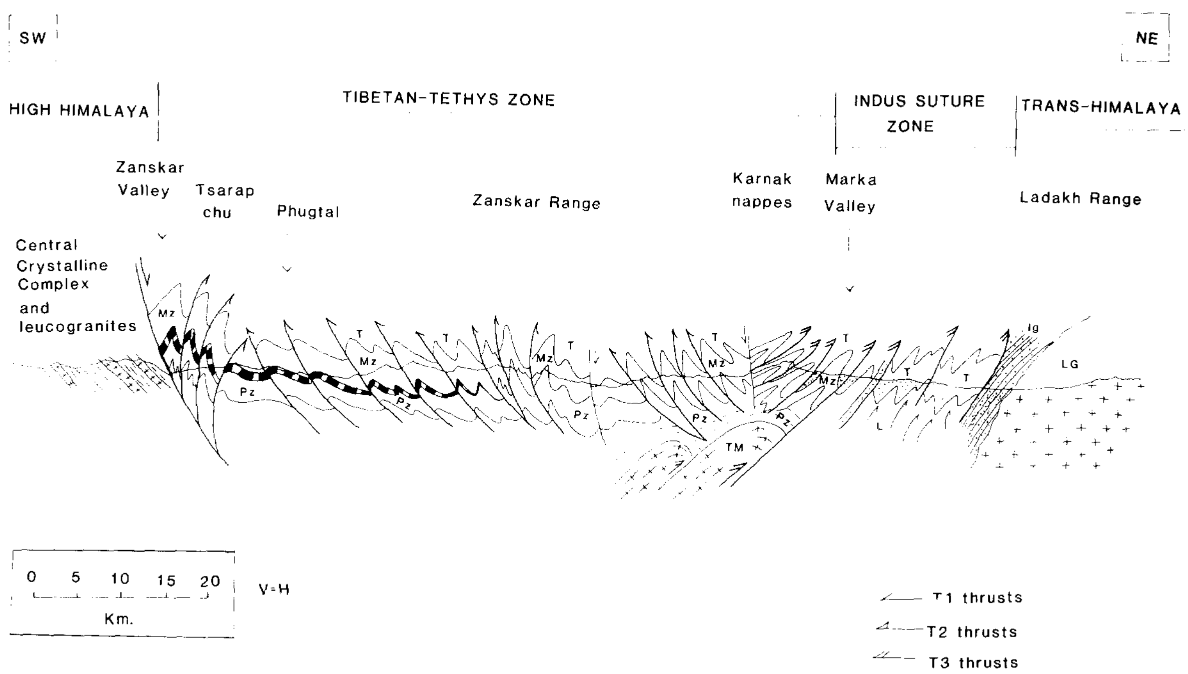

Fig. 7. Stuctural cross-section across the Zanskar Range east of the Zanskar River gorge. Symbols and ornament are the same as for Fig. 6. Line balancing on the Cretaceous–Tertiary boundary shows that the present 98 km length from the Zanskar Valley normal fault to the Ladakh batholith restores to an original length of 224 km, so that shortening is 126 km. The upright and NE-facing folds around the Tsarap Chu on the hangingwall of the Zanskar Valley normal fault are interpreted as dorsal culmination collapse features which have effectively inverted the original SW-verging folds and thrusts.

formation of the Palaeocene Yamdrock melange occurred between the ophiolite and the shelf margin (Allegre *et al.* 1984, Searle *et al.* in review). Shackleton (1981) interpreted this mélange as a trench mélange formed in a subduction zone which accumulated Mesozoic and Permian material scraped off the downgoing slab.

CONTINENTAL COLLISION STAGE (T2)

The Tibetan-Tethys zone of the Zanskar Mountains consists of sedimentary rocks of the northern Indian continental margin, ranging in age from Cambrian to Eocene (Fig. 3). These rocks have been affected by polyphase thrusting and intense tight to isoclinal folding (Fig. 8a). Folds formed during the early collision phase all face S or SW, and the thrusts are S- or SW-directed.

The collision between India and Asia probably occurred between 50 and 36 Ma ago; that is, during Eocene time (Molnar & Tapponier 1975, Patriat & Achache 1984). This is based on the rapid decrease in velocity of the northward drift of India indicated by marine magnetic anomalies in the Indian Ocean (McKenzie & Sclater 1971), and the change in sedimentation in the Indus suture zone from marine 'flysch' to continental molasse (Frank *et al.* 1977a, Searle 1983a). At about 40 Ma clasts of Ladakh granitoid and andesitic volcanic material derived from the north appear in the Hemis conglomerates (Fig. 4), together with carbonate clasts derived from the Zanskar shelf to the south. The major phase of crustal shortening in the Tibetan–Tethys and Indus suture zones was post-Eocene (Fig. 4), immediately after the continental collision and the closure of Tethys. There are no deep water Tethyan marine sediments younger than Maastrichtian–Danian (lowermost Palaeocene) and a post-Eocene age of obduction of the Spontang ophiolite is therefore highly unlikely. Deformation and internal strain increases dramatically northwards across the Tibetan–Tethys zone in the Zanskar mountains. In the south-west around Padam and Zangla upright, tight folds in the Palaeozoic and Triassic sediments are separated by steeply dipping thrust faults (Fig. 10a). In the central part of the Zanskar Range around Nerak and Yulchung intense isoclinal folds affect the shelf carbonates, and numerous thrust faults can be seen in the magnificent 3-D exposures along the Zanskar River gorge (Figs. 8b & c, 9 and 10b).

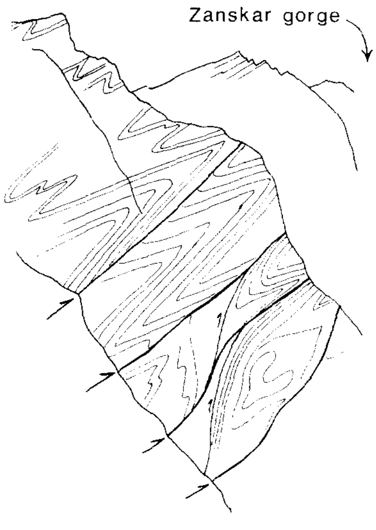

Fig. 9. Sketch of the 500 m cliff section above Yulchung village in central Zanskar shown in Fig. 8 (b) showing extreme amounts of crustal thickening by folding and thrusting in Triassic shelf carbonates of the Zanskar Supergroup.

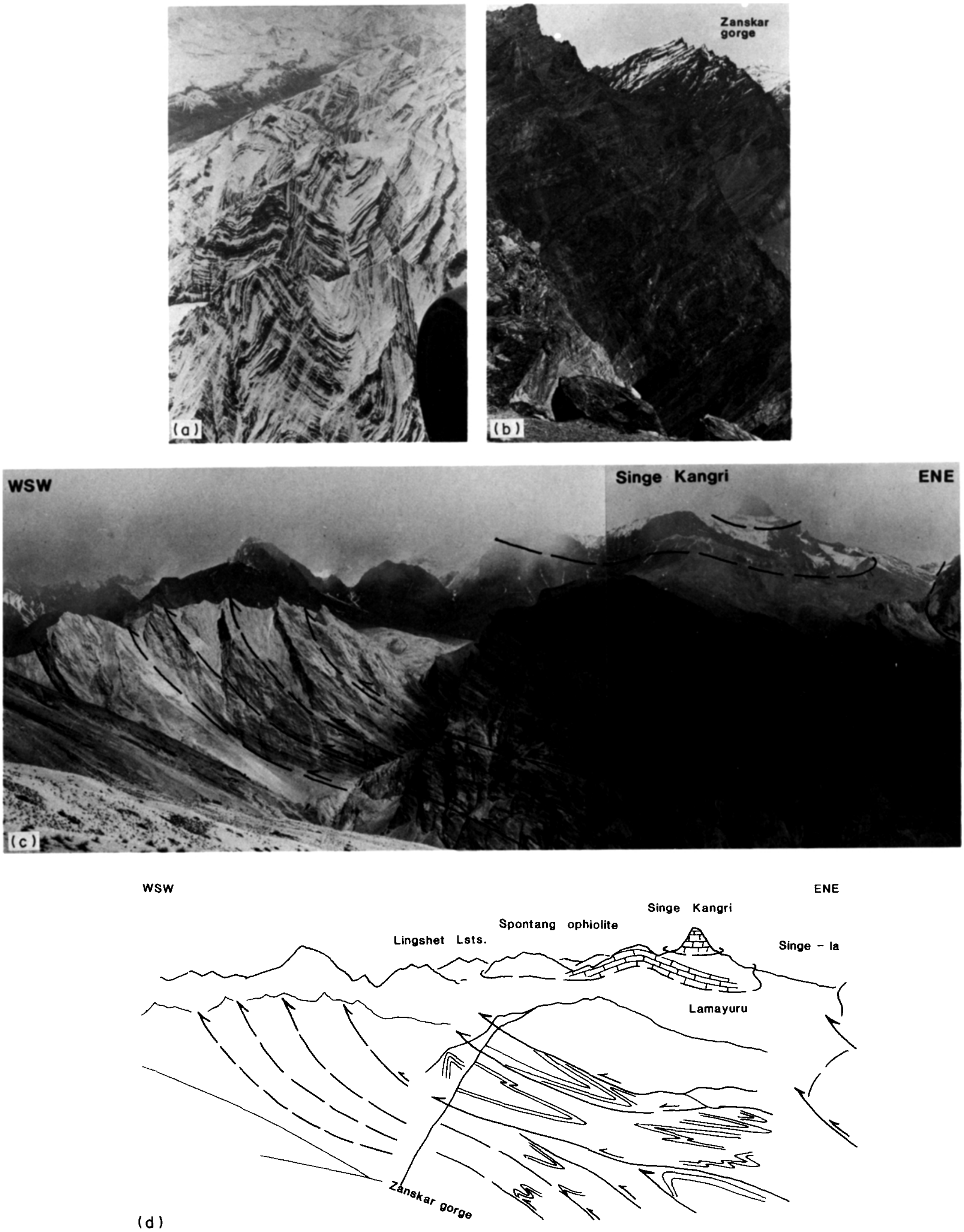

Fig. 8 (a) Aerial photograph of tight folds in the Palaeozoic to Lower Mesozoic sediments in the high mountains south of the Spiti Valley. (b) En échelon tight to isoclinal folds and thrusts in Triassic Kioto Formation limestones in 500 m high cliff sections near Yulchung, central Zanskar mountains (see also Fig. 9). (c) Tectonic stacking order seen in the 2400 m relief cliffs along the northwest side of the Zanskar River gorge from above Nerak village. The Zanskar shelf carbonate sequence shows intense isoclinal folds and thrusts and an imbricate fan structure in the lower 1000 m. Lamayuru sediments tectonically overlie the shelf sequence and were emplaced with the Spontang ophiolite (hidden in far distance) during the Palaeocene. Cliff-forming Lingshet limestones and neo-autochthonous (T1) Eocene limestones unconformably overlie Lamayuru thrust sheets. A late stage (post Eocene T2) leap-frog thrust (the Photoksar thrust) on the far right thrusts originally lower Triassic shelf carbonates over originally higher allochthonous (T1) Lamayuru thrust sheets, reversing the earlier T1 stacking order, and truncating earlier T1 folds and thrusts in the footwall. (d) Interpretation of (c).

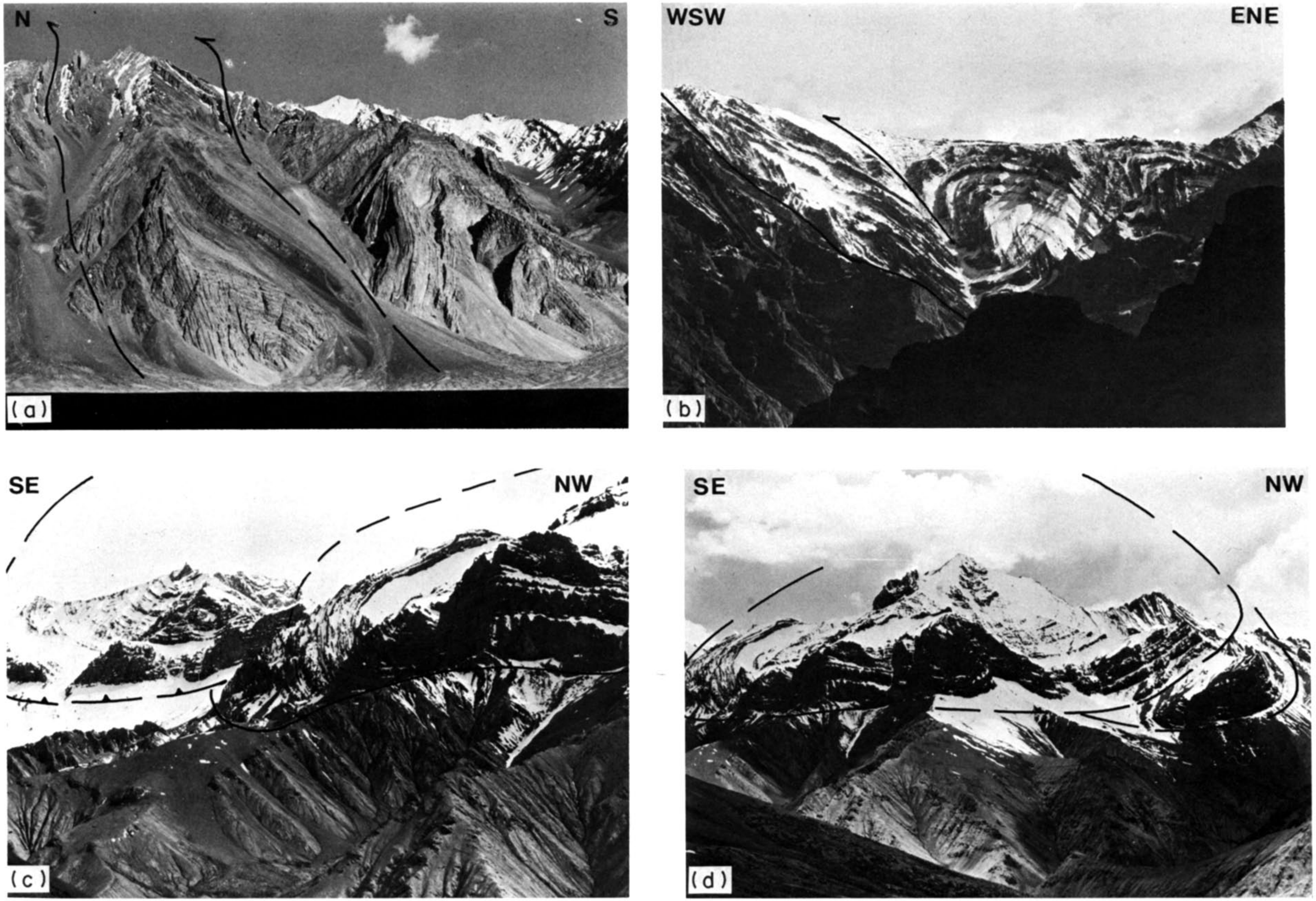

Fig. 10. (a) Folds and thrusts in Triassic sediments south of Zangla and north of Padam, with listric axial planes and vertical thrust planes. Height of mountain tops is approximately 300 m above the Zanskar Valley. (b) Box folds associated with SW-directed thrusts exposed in 500 m high cliff-sections on the west bank of the Zanskar River, north of Nerak. (c) Lateral section through the leading edge of a Helvetic-type nappe near Karnak. Mesozoic shelf carbonates in Rubering-Ri, north of Rubering-la, 30 km south of the Marka Valley. Vertical height of photo is approximately 1000 m. (d) Isoclinally folded Mesozoic shelf carbonates of the upper Karnak nappe overlying the Rubering-Ri nappe. The photo shows an oblique to lateral section across a NE-verging and NE-closing nappe, formed during the late stage (T3) backthrusting phase along the northern margin of the Tibetan–Tethys zone. Vertical height shown is approximately 1000 m

In the Marka-Zangla cross-section (Fig. 7) around the Rubering-la and Zalung Karpo-la passes near Karnak, huge recumbent folds (Figs. 10c & d) resemble the Helvetic nappes of the Swiss Alps (Ramsay *et al.* 1983). In the Karnak region south of the Marka Valley (Fig. 2) the thrusts are steeply dipping. South of this the folds are SW-facing and the large nappe structures SW-verging. Fold axial planes and thrust faults gradually steepen northwards towards Karnak to become vertical and overturned to the N and NE. This fan pattern is thought to be the result of progressive steepening due to continued shortening after initial thrusting. The backthrusting zone affects the whole Indus suture zone and the northern margin of the Tibetan–Tethys zone along the length of the Trans-Himalaya in Ladakh and Tibet (but not westwards in Pakistan), and is discussed in the following section (T3).

Late stage rethrusting of the Zanskar shelf sediments can also be demonstrated. Late thrusts cut up section through the previously assembled allochthon putting originally (T1) lower tectonic units over originally higher tectonic units These 'leap-frog' thrusts (Searle 1985) are again caused by continued shortening after initial thrust stacking. The Photoksar thrust (Fig. 6) is a major fault bounding the north and north-east margin of the Spontang (T1) thrust sheets. Triassic–Lower Jurassic shelf carbonates are rethrust southwards (T2) over previously emplaced (T1) Spontang thrust sheets, effectively reversing the T1 stacking order (Fig. 8c). West of Lingshet the Spontang and Lamayuru thrust sheets tectonically overlie the Mesozoic shelf carbonates and the Campanian–Maastrichtian Kangi-la Formation along early (T1) thrusts.

High-Himalayan deformation

The climax of Himalayan deformation, metamorphism and granitization in the central crystalline complex of the High Himalaya can be related to crustal subduction and ductile shearing along the Main Central Thrust (MCT) zone in the Oligocene–Miocene (LeFort 1975). Rb–Sr and K–Ar ages indicate a thermal peak of metamorphism between 40 and 30 Ma and give Miocene–Pliocene cooling ages (Frank *et al.* 1977b, Andrieux *et al.* 1977). The Manaslu anatectic granite in Nepal has a U–Pb isochron of 18.1 ± 0.5 Ma (^{87}Sr/^{86}Sr = 0.7470) (Deniel *et al.* 1983). Other High Himalayan leucogranites from Nepal (LeFort 1973, 1975, Vidal *et al.* 1982) and the Zanskar, Kishtwar and Kulu Himalaya of India (Searle & Fryer 1985) have similar young ages. Honegger *et al.* (1982) quote Rb–Sr mica cooling ages of 26.6 to 11.6 Ma for the S-type granites in the Suru Valley, Zanskar. Inversion of metamorphic isograds is associated with large-scale S-directed ductile shearing along the MCT (LeFort 1975, Pecher 1977). In the High Himalaya south of the Zanskar Valley large S- and SW-vergent nappes and S- and SW- directed thrusts are responsible for the inverted metamorphic sequence (Searle 1983b).

Culmination collapse and normal faulting

The Zanskar Valley is a 100 km long valley separating sillimanite and kyanite grade metamorphic rocks, migmatites and anatectic granites of the High Himalaya to the south, from unmetamorphosed to lower greenschist facies sediments of the Tibetan–Tethys zone to the north. The tectonic contact dips N and is probably a listric normal fault (dorsal culmination collapse) associated with thrust culmination of the High Himalaya. Upright or N-facing folds in the Padam area (Fig. 10a) may reflect gravity collapse features on the hangingwall of the normal fault.

South of Padam and around Ghumbur Ranjung mountain in the eastern part of Zanskar (Searle & Fryer 1985), garnet–muscovite–tourmaline bearing granites lie immediately south of the contact. The metamorphic grade and geothermometers on coexisting magmatic garnet and biotite show that these rocks formed at depths in excess of 15–20 km (650–700 °C, at 6–8 kb). K–Ar age determinations on muscovite separates from these granites and migmatites along the Zanskar Valley give cooling ages of 22 ± 1–30 ± 2 Ma (D.C. Rex pers. comm.). Unroofing of these anatectic granites and migmatites occurred during rapid thrust culmination of the High Himalaya since the late Oligocene–Miocene. The large-scale listric normal fault along the Zanskar Valley may have had a total amount of throw in excess of 7–10 km, but may also have been active throughout the Tertiary thrust culmination of the High Himalaya. Similar normal faulting north of the High Himalaya has also been reported in the Annapurna region of central Nepal (Caby *et al.* 1983), and in southern Tibet (Burg *et al.* 1984a).

POST-COLLISION STAGE (T3)

Tertiary continental molasse sediments (Indus Group), comprising thick well-bedded boulder conglomerates interbedded with coarse sandstones and thin shales, crop out along the length of the Indus–Tsangpo suture zone. In Ladakh the basal part of this 4 km thick unit unconformably overlies the Ladakh (Trans-Himalayan) granitoids. Precise dating of these molasse deposits is not available but they appear to span late Eocene to Miocene (Frank *et al.* 1977a, Thakur 1981).

Along the southern margin of the batholith the unconformably overlying molasse sediments are steeply dipping (Searle 1983a, fig 6f). Further south, the Indus Group is clearly folded and thrust towards the north. The southern contact of the molasse near Kargil at Pushkum is a S-dipping backthrust putting Cretaceous Dras volcanics over Tertiary Indus molasse (Searle 1983a, fig. 6e). This backthrusting appears to be very late stage and postdates the Indus group.

Practically all tectonic contacts in the Indus suture zone in Ladakh separating Lamayuru complex rocks, Dras Volcanic rocks and ophiolitic mélange zone rocks now dip steeply S. The N-directed backthrusts are parallel to the thrusts affecting the Indus molasse and are probably also late stage. The southern contact of the Indus suture zone is a major N-directed backthrust putting Mesozoic Zanskar shelf carbonates over suture zone rocks, inverting the earlier stacking order (Fig. 6).

During the Tertiary two molasse basin foredeeps developed: the Indus–Tsangpo basin north of the Himalaya and the Siwalik basin south of the Himalaya. The Main Boundary Thrust (MBT) is presently active, and thrusts the whole Himalaya piggy-back fashion S over Pliocene–Pleistocene Siwalik molasse. Asymmetric S-verging folds within the Miocene to present day Siwalik molasse indicate the probability of blind thrusts (Main Frontal thrust system) extending at depth south of the Main Boundary Thrust (Seeber *et al.* 1981). In Pakistan, the equivalent Hazara thrust puts Indian plate gneisses and Mesozoic sediments over Eocene–Miocene molasse (Coward 1983).

Fault-plane solutions of recent earthquakes are consistent with active thrusting along the MBT and MFT zones (Seeber & Armbruster 1979, Seeber *et al.* 1981). Earthquake epicenters at 10–30 km depths in the Hazara region of Pakistan indicate a shallow NE-dipping thrust fault along the Indus–Kohistan seismic zone (IKSZ), along which the crust of the Indian Shield is underplating the southern flank of the Himalaya (Seeber & Armbruster 1979, Coward 1983). Gravity anomalies show that the crust thickens to the north and that the Moho steepens dramatically beneath the High Himalaya (Molnar 1984). However, fault plane solutions of recent earthquakes in the Tibetan–Tethys zone in the Tso Morari area (Fig. 2) and in SW Tibet, north of the High Himalaya, indicate normal faulting and E–W extension similar to the present day tectonics of the Tibetan plateau (Molnar & Tapponier 1975, 1978, Molnar 1984).

DISCUSSION

Balanced cross-sections: constraints

Cross-section balancing is undoubtedly an essential tool for unravelling the structural history of any thrust terrain. They should however be used and interpreted with extreme caution in the highly complex internal parts of mountain belts such as the Himalaya. Even in relatively simple foreland fold and thrust belts such as the Salt Ranges of North Pakistan (Coward & Butler 1985) one or two inferences can drastically influence the end product. For example there are no *accurate* criteria to decide at what depth to draw the basal detachment, or at what angle the sole thrust dips N beneath the Himalaya. Both of these factors will radically affect the original area or length of any section restored.

Cross-sections that are perfectly balanced and restored imply that the complete structural history has involved piggy-back thrusting, where thrusts propagate successively towards the foreland and no stratigraphic section has been eliminated. Where stratigraphic section has been eliminated by 'out-of-sequence' thrusting, some inference has to be made to make the section balance. In highly complex thrust belts such as the Zanskar and Ladakh Mountains, the amount of inference (fiddling) that has to be made is at present unacceptably great.

The Ladakh and Zanskar mountains show at least three major periods of crustal shortening during the whole history of the Himalayan orogeny. Any restored cross-section must not only be balanced geometrically, it must also be balanced progressively in reverse time sequence. The fourth dimension, time, must be incorporated into these restored sections. The present state of the art in the Himalaya can only distinguish the major timing of motion on thrusts. More detailed structural mapping in conjunction with stratigraphically dated sections is needed to construct multi-stage, four-dimensional restored sections.

Deep structure of Zanskar: constraints

The deep structure of the Zanskar Range is extremely difficult to determine because of three major factors. Firstly, the intense complexity of thrust geometry (see for example Figs 8b & c) makes prediction of unexposed deep structure almost impossible. Secondly there is an abundance of late stage 'leap-frog' thrusts such as the Photoksar thrust (Fig. 6) and the Tso Morari thrust (Fig. 7) which cut through a previously stacked pile of thrust sheets. The throw on the Photoksar thrust is at least 4 km and probably much greater in reality. The Tso Morari thrust brings lower or mid-crustal rocks to the surface and must have a throw well in excess of 5–10 km. These 'leap-frog' thrusts are major late-stage re-imbrication features that cannot be related to smaller-scale breaching processes (Butler 1983, Butler & Coward 1984). Some unknown volume of stratigraphic section has been tectonically eliminated where trailing edges of earlier thrusts are cut off along the footwall of later 'leap-frog' thrusts (Fig. 8c). Finally, trailing edges of the steep thrust sheets between the Spontang ophiolite and the Indus suture zone are nowhere seen. The depth at which cut-offs or branch lines are drawn will obviously affect the restored width of section and the deep structure of the Zanskar Mountains.

The Tso Morari crystalline rocks in Eastern Ladakh (Fig. 2) show a domal structure cored by high-grade sillimanite gneisses, amphibolites and S-type granites with metamorphism decreasing upward and outward (Thakur & Virdi 1979, Thakur 1981). Permian conodonts have been discovered in the Upper Taglang-la group (Virdi *et al.* 1978). The Tso Morari rocks are interpreted here as a major Late Tertiary culmination of mid-crustal rocks brought to high structural levels on the hanging-wall of a major 'leap-frog' thrust, that is the Tso Morari thrust. It is analogous to the Kangmar granite–gneiss dome of the so called North Himalayan belt in southern Tibet (Burg *et al.* 1984b).

CONCLUSION

The Ladakh and Zanskar Himalaya show an extremely complex thrust geometry which results from three major periods of thrust faulting and crustal thickening. These can be summarized as follows.

T1 (75–60 Ma). During the Campanian relatively stable shelf carbonate sedimentation on the north Indian shelf and margin abruptly ceased. A foredeep developed along the margin accumulating thick shales and olistostrome deposits into which the Lamayuru complex and Spontang ophiolite thrust sheets were emplaced. This early stage (pre-continental collision) has largely been obscured or overprinted by strong mid-Tertiary thrusting during the following stages and is preserved only as earlier structures within late thrust-bounded duplexes. Upper Palaeocene and Lower to Middle Eocene shallow marine carbonates were deposited unconformably on top of the deformed Zanskar shelf carbonates.

T2 (45–25 Ma). Following Eocene collision of the Indian and Karakoram (Chang Tang) plates, S- and SW-thrusting of the Indus suture, Tibetan–Tethys and High Himalayan zones occurred. A southward foreland-propagating sequence carried the Spontang and Lamayuru (T1) thrust sheets piggy-back. This thrusting affects the complete Palaeozoic, Mesozoic and Eocene stratigraphy of the north Indian plate margin. In the High Himalaya duplexes of Precambrian basement and Phanerozoic cover doubled the crustal thickness causing Barrovian metamorphism, crustal anatexis and production of anatectic S-type leucogranites and adamellites.

Culmination collapse north of the High Himalaya probably occurred synchronously with rapid thrust culmination in the High Himalaya itself, and the listric normal fault along the Zanskar Valley may have a total throw of about 7 km. Late-stage leap-frog thrusts rethrust the previously stacked pile, and caused further inversion of the T1 stacking order. Previously lower Mesozoic shelf carbonates in Zanskar are rethrust southwestwards over Spontang–Lamayuru T1 Thrust sheets. A rapidly subsiding molasse basin developed along the Indus suture zone during late Eocene–Miocene time and at about 40 Ma clasts in the molasse were derived both from the Ladakh batholith to the north and the Zanskar shelf to the south. Tethys had finally closed.

Thrusting propagated southward across the High Himalaya where the MCT ductile shear-zone emplaces lower crustal leucogranites, migmatites and sillimanite–kyanite grade metamorphic rocks S over the low-grade metamorphics and sediments of the lesser Himalaya. An inverted metamorphic sequence was formed either by S-directed recumbent folding of isograds after metamorphism in the High Himalaya (Searle & Fryer 1985), or by thrusting a hot upper plate (Tibetan Slab) over rocks of the Lesser Himalaya (Le Fort 1975).

T3 (<15 Ma). The continuing motion of the Indian plate into the Asian plate at about 10–20 mm a^{-1} (Molnar 1984) has caused late Tertiary thrusting along the Indus suture zone and the northern margin of the Tibetan–Tethys zone. A 20–30 km wide belt of steep and N-directed backthrusts has resulted in a crustal scale pop-up structure. Many steep thrust faults have subsequently become strike-slip faults during Late Tertiary to Recent time.

This late-stage collision-related thrust faulting is shown in both the Late Tertiary molasse basins: the Indus basin north of the Himalaya and the Siwalik basin south of the Himalaya. Active S-directed thrusting is occurring all along the southern margin of the Himalaya along the MBT zone and Siwalik Hills.

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