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Changing mechanical response during continental collision: active examples from the foreland thrust belts of Pakistan

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Abstract—We have used data from teleseismic, seismic reflection and field geologic studies, along with both geomechanical and gravity modeling to contrast the tectonics of four active orogenic wedges in Pakistan: the Kashmir Himalaya, the Salt Range–Potwar Plateau foldbelt, the Sulaiman Range and the Makran accretionary wedge.

In Makran, oceanic crust is still being subducted, and a thick pile of sediments is being accreted and underplated. Undercompaction and excess pore pressures can explain the narrow cross-sectional taper and frontal aseismicity of this wedge. Beneath the Sulaiman wedge, continental crust is just starting to be underthrust. Indirect evidence suggests that fine-grained carbonate rocks found in abundance deep in the stratigraphic section may be deforming ductilely at the base of the Sulaiman wedge and provide a zone of ductile detachment. The collision has proceeded to a much more mature stage in the Salt Range–Potwar Plateau foldbelt and the Kashmir Himalaya. Isostatic response to underthrusting of continental crust has kept the sedimentary pile quite thin in both of these wedges, so in that respect the two foldbelts are similar. However, thick Eocambrian salt beneath the Salt Range and Potwar Plateau permits that foldbelt to be much wider in map view, with a thinner cross-sectional taper and a mixture of thrust vergence directions. A major normal fault in basement causes the Salt Range to rise in front of the mildly deformed molasse basin of the southern Potwar Plateau.

Much of the diversity among these mountain belts can be understood in terms of differences in the maturity of the collision process in each area, the resulting thickness of the sedimentary pile encountered at the deformation front, and the presence or absence of large contrasts in strength between the various layers of the stratigraphic section and basement relief.

INTRODUCTION

THE collision of the Indian plate with Asia is producing a remarkable variety of active fold-and-thrust wedges within Pakistan. These zones extend from the Kashmir fold-and-thrust belt southwestward to the Salt Range–Potwar Plateau foldbelt, the Sulaiman foldbelt, and the Makran accretionary wedge (Figs. 1 and 2). The last three are all very wide (approximately 150, 200 and 300 km, respectively), as compared to the narrower thrust zone in Kashmir (less than 100 km). In this paper, we compare the structural styles of all four of these thin-skinned wedges and we offer some possible mechanical explanations for differences among them.

The Makran wedge is a sediment-rich accretionary prism in which high pore-fluid pressures have long been known to exist (e.g. Ahmed 1969). The weakened resistance to sliding that accompanies high pore fluid pressures is a likely explanation for the enormous width and narrow cross-sectional taper of this wedge (Davis *et al.* 1983, Platt 1990). Much of the Sulaiman lobe remains relatively poorly explored and its tectonics are not well understood. However, deformation there is, undoubtedly influenced by the extreme thickness of the sedimentary section: the depth to the top of Jurassic strata is approximately 10 km at the deformation front near Sibi, and the depth to crystalline basement in much of the foldbelt may be as much as 20 km (Banks & Warburton 1986). The Salt Range–Potwar Plateau foldbelt is underlain by an Eocambrian evaporite. The relationship between the distribution of this salt layer and the advance of the deformation front into the foreland has been appreciated for some time (e.g. Sarwar & De Jong 1979, Seeber *et al.* 1981). Unlike these three broad zones of thin-skinned thrusting, the Kashmir belt is narrow with a relatively high cross-sectional taper, a geometry that suggests strong coupling between the sediment wedge and the underlying autochthon (e.g. Chapple 1978, Davis *et al.* 1983).

The fold-and-thrust wedges of Pakistan exhibit a wide variety of tectonic styles which make them ideal for contrast and comparison directed towards improving understanding of thin-skinned contraction. The continental collision is happening today, so many of the geodynamic modeling constraints that are inaccessible for most other foldbelts, however well studied, are available for the mountain belts of Pakistan. There is very good surface exposure, and oil and gas exploration activities have produced a large volume of subsurface information. The extreme breadth of the Sulaiman

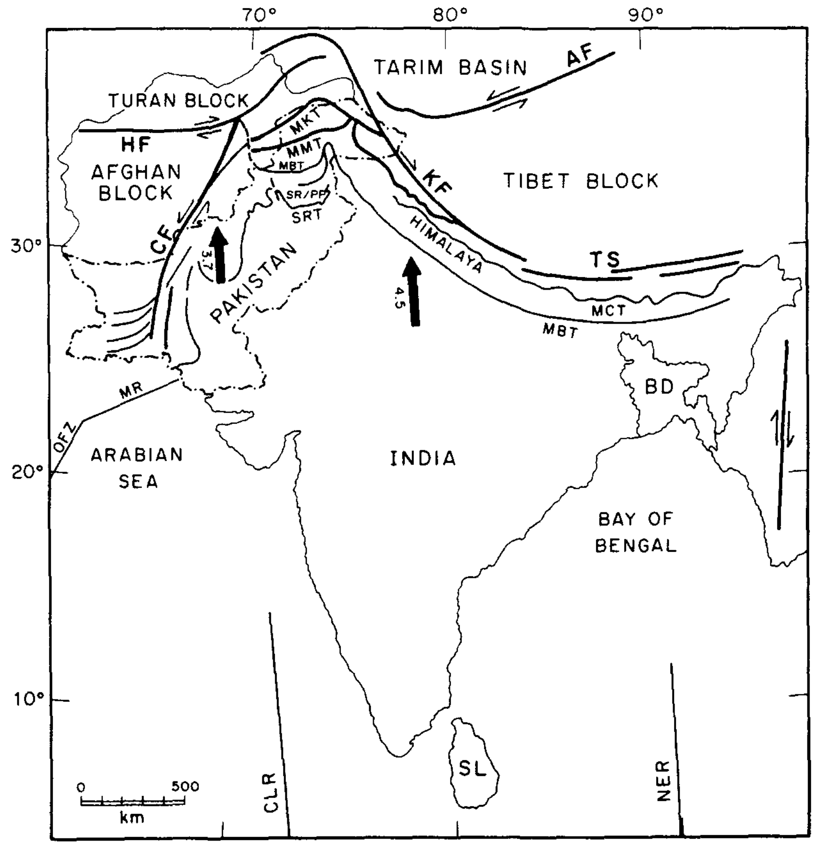

Fig. 1. Tectonic sketch map showing Himalayan collision zone and motion of India relative to Asia (in cm year^{-1}, after Jacob & Quittmeyer 1979). The thrust belts discussed in this paper are located in the northwestern portion of Pakistan. AF = Alltyn Tagh Fault, BD = Bangladesh, CF = Chaman Fault, CLR = Chagos–Laccadive Ridge (Reunion Hotspot), HF = Herat Fault, KF = Karakoram Fault, MBT = Main Boundary Thrust, MCT = Main Central Thrust, MKT = Main Karakoram Thrust, MMT = Main Mantle Thrust, MR = Murray Ridge (Kerguelen hotspot), OFZ = Owen fracture zone, SL = Sri Lanka, SR/PP = Salt Range–Potwar Plateau, SRT = Salt Range Thrust, TS = Tsangpo suture. After Jaswal (1990).

wedge and the great thickness of the sediments within it are reminiscent of the Verkhoyansk foldbelt in Siberia (e.g. Churkin 1972, Nalivkin 1973) and the Ouachita Mountains of the southern United States (e.g. Nelson *et al.* 1982, Lillie *et al.* 1983). Thus, the availability of data on the structures and seismicity of the active Sulaiman wedge may afford an opportunity to learn indirectly about these inactive foldbelts. Likewise, a study of the Salt Range provides insights on the effects of factors such as basement topography and the thickness and depth of the salt on the tectonics of foldbelts that are no longer active, such as the Pennsylvania Plateau of the Appalachians.

In contrast to the foldbelts such as the Kashmir Himalaya, in which there is believed to be a large shear traction at the base of the overthrust belt (Fig. 3a), there are at least two fairly common ways in which a very weak detachment layer can be formed in a compressional, thin-skinned wedge. A number of investigators have concluded that deformation at the frontal toe and along the basal detachment of at least some accretionary prisms occurs under conditions of elevated pore pressures and, presumably, very low shear stresses (e.g. von Huene & Lee 1982, Moore & Biju-Duval 1984). Results of oil-industry drilling and the presence of numerous mud volcanoes suggest that the Makran wedge is a prime example of an overpressured accretionary wedge (Fig. 3e). The second class of weak-detachment, contractional wedges includes those fold-and-thrust belts that overthrust, at least in part, a detachment zone in an evaporitic layer. Because of the ductility and weakness of evaporites, they share several readily observable characteristics that are different from those typical of mountain ranges without evaporites (Davis & Engelder 1985). The Salt Range–Potwar Plateau foldbelt is a prime example of this type of thin-skinned contractional wedge (e.g. Lillie *et al.* 1987), illustrated in Figs. 3(b) & (c). In particular, the presence of a weak detachment zone in evaporites permits a thrust belt to have an extremely narrow cross-sectional taper and deformation with a marked lack of consistent vergence in its structures. A speculative third class of wide foldbelt with weak mechanical coupling along its base consists of those in which the sedimentary section is sufficiently thick to allow non-evaporitic sedimentary rocks to behave in a ductile manner, deforming in a time-dependent fashion under modest shear stresses (Fig. 3d). It is reasonable to assume that if any modern foldbelt fits this description, it would be the Sulaiman foldbelt, with its very thick sedimentary column.

The diversity that exists among the foldbelts of Pakistan is easily noted in the topographic profiles of these mountain belts. The relatively steep and narrow profile of the Kashmir Himalaya (Fig. 4a) resembles that of parts of the Andes (e.g. Jordan *et al.* 1983) and western Taiwan (e.g. Suppe 1980). In contrast, topographic slopes are quite subdued in the eastern Potwar Plateau (Fig. 4b) and, north of the 800 m of relief in the Salt Range, in the central and western Potwar Plateau (Fig. 4c). The Sulaiman wedge has locally impressive topographic relief, particularly near the front of the foldbelt, but the regional surface slope farther north and west is gentle (Fig. 4d). Although the Makran accretionary wedge is over 300 km wide, its rear is only 5–6 km higher than the deformation front, so the mean surface slope is only a bit over 1° (Fig. 4e).

Lillie (in press) has calculated a sequence of density models for an idealized continental collision, illustrating both the overall geometric development under Airy conditions (e.g. Fig. 5) and the resulting gravity signature of the orogen. In terms of the overall structure and thickness of the crust, the thrust belts of Pakistan may be thought of as being on a continuum, with Makran (Figs. 5a & b) as the immature end-member and the Salt Range–Kashmir region (Fig. 5d) at the mature end of the spectrum. Both the thickness and nature of the strata within the wedges vary with the degree of continental underthrusting. The Makran is an accretionary wedge over oceanic crust, with enormous quantities of continentally derived sediments over a thinner pelagic sequence. The Sulaiman, a very thick wedge consisting of a passive margin sequence overlain by flysch and molasse, is located over the transition zone between continent and ocean (Fig. 5c). In contrast, the Salt Range–Potwar Plateau and Kashmir foldbelts include much thinner cratonic strata and molasse over continental crust. By controlling the thickness and type of sediments available for inclusion in each of these contractional wedges, the contrast in degrees of collision has a major effect on the tectonics of these foldbelts, and may explain some of the fundamental differences among them.

In the following sections of this paper, we describe some of the ways in which the Salt Range–Potwar Plateau, Makran and Sulaiman contractional wedges differ from the Kashmir wedge and from each other, and we will propose mechanical explanations for varied lithologies and rheological behaviors found within the

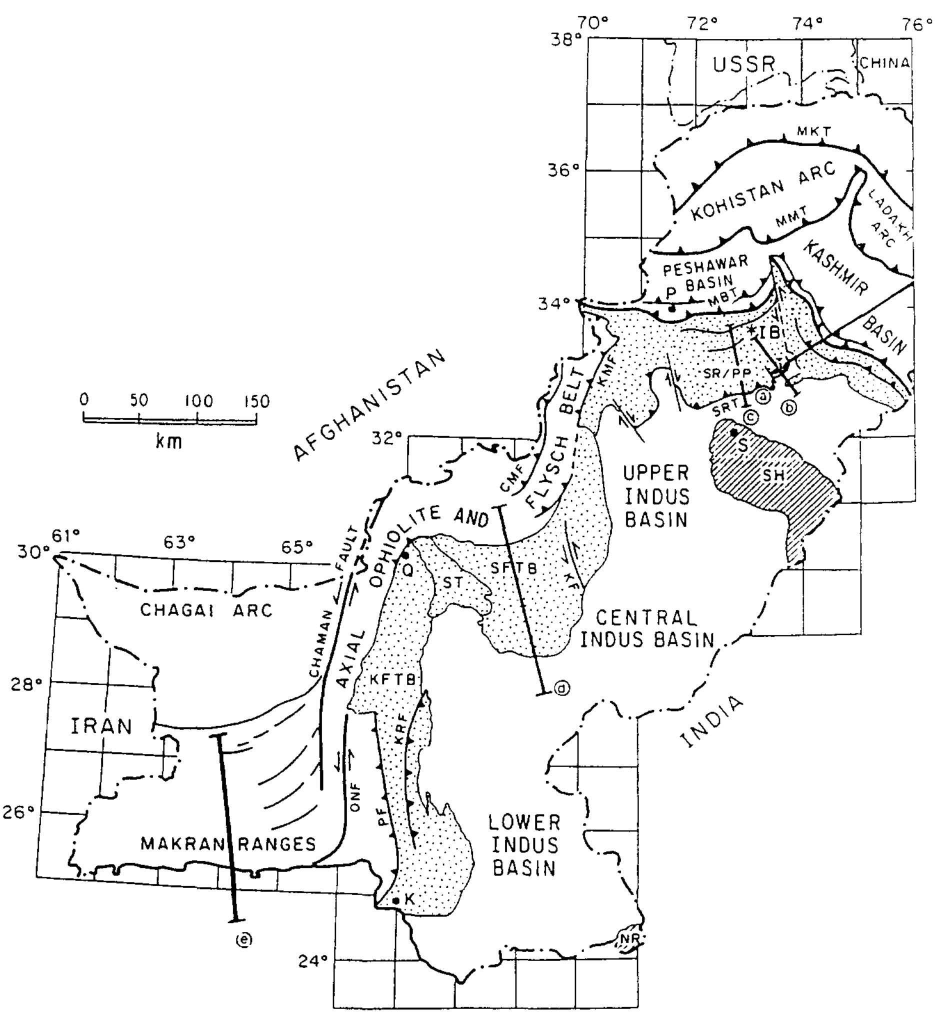

Fig. 2. Generalized tectonic map of Pakistan emphasizing active foreland thrust belts (stippled) and the location of the Makran accretionary wedge. Note positions of cross-sections (a)–(e) portrayed in Fig. 7(b). CMF = Chukhan Manda Fault, IB = Islamabad, K = Karachi, KF = Kingri Fault, KFTB = Kirthar foreland fold-and-thrust belt, KMF = Kurram Fault, KRF = Kirthar Fault, NR = Nagarparkar ridge, ONF = Ornach Nal Fault, P = Peshawar, PF = Pab Fault, Q = Quetta, S = Sargodha, SFTB = Sulaiman foreland fold-and-thrust belt, SH = Sargodha basement high, SR/RP = Salt Range–Potwar Plateau, SRT = Salt Range Thrust, ST = Sibi trough. Modified from Jaswal (1990).

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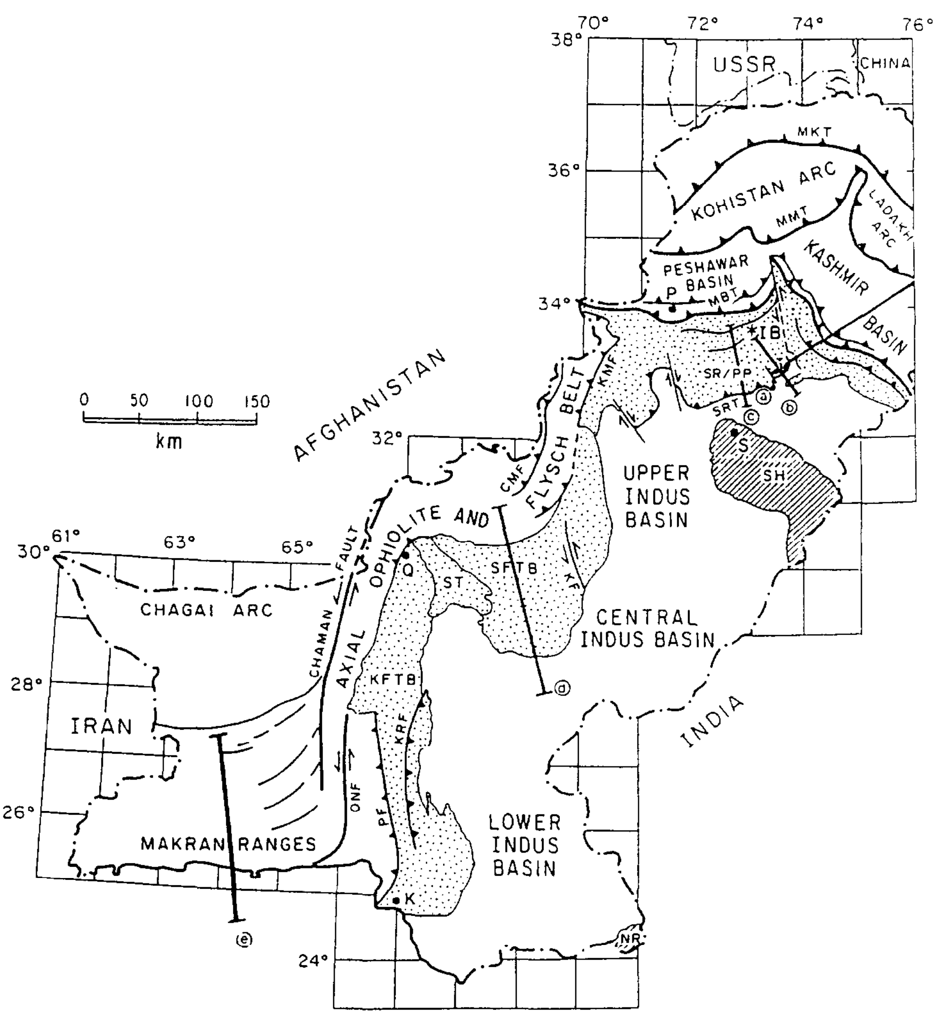

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south of the Kashmir Basin is about 60 km wide, but within that zone it nonetheless attains an overall height exceeding 3 km (Figs. 2, 4a and 6). The most frontal thrusts show Holocene slip, consistent with a generally forward progression of the locus of active thrusting (e.g. Yeats & Lillie 1991).

Simple models for the mechanics of the thin-skinned mountain belts can explain the overall shape of the active foldbelt, the general forward progression of deformation with time, and the consistent forward vergence of structures within it in terms of the magnitude and sense of the shear coupling along the foldbelt's basal décollement (e.g. Chapple 1978, Davis *et al.* 1983). If we assume that the failure of rocks in the upper half of the crust is governed by friction, then the development of a contractional wedge with significant topography is predicted if the décollement layer is only moderately weaker than the rocks above it (Fig. 3a). In Taiwan, a frictional strength difference of only about 20% is sufficient to allow sliding at a critical taper of about 9° (Davis *et al.* 1983, Dahlen *et al.* 1984).

The presence of significant traction along a basal thrust zone has an important effect upon the stress field within the allochthon above it (e.g. Hafner 1951). Basal traction causes the axis of maximum principal compressive stress to dip towards the foreland at an angle comparable in magnitude to the wedge taper; indeed, in the limiting case of a cohesionless frictional wedge, the two are precisely equal (Dahlen 1984). Thus, forward-vergent thrusts (dipping toward the hinterland) tend to have shallower dips than backthrusts and are energetically favored over backthrusts (Figs. 3a and 6a).

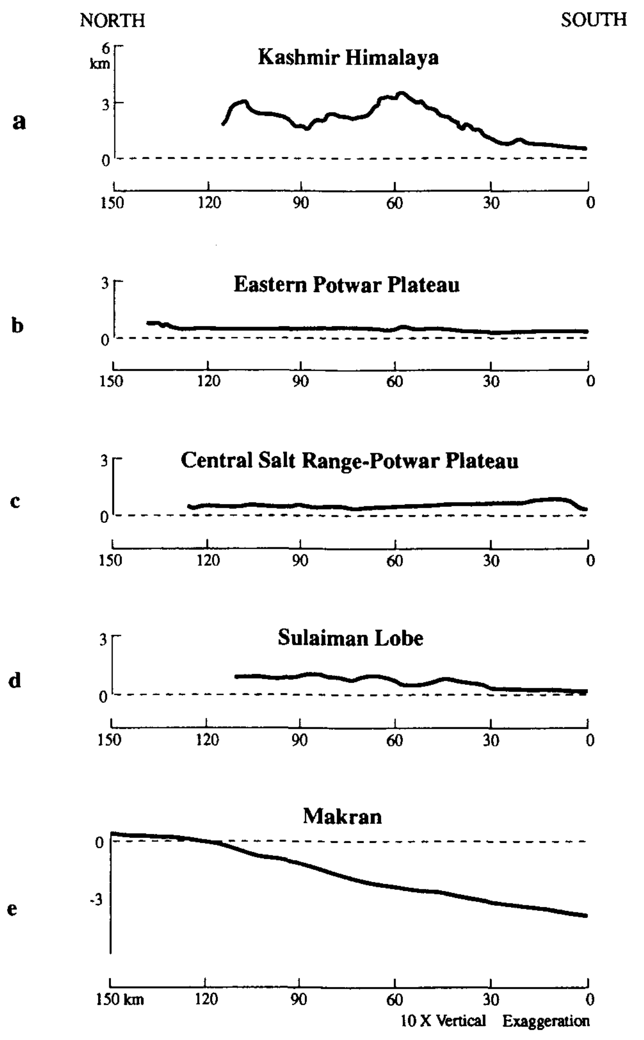

Fig. 4. Topographic profiles across the foldbelts of Pakistan (a–d after Jaumé 1987). (a) Kashmir Himalaya. (b) Eastern Potwar Plateau. (c) Central Potwar Plateau and the Salt Range. (d) Southern Sulaiman wedge. (e) Makran accretionary wedge near longitude 63°E (after Byrne *et al.* 1992).

SALT RANGE–POTWAR PLATEAU

The Salt Range–Potwar fold-and-thrust belt of the northern Pakistan (Fig. 2) is a currently active foldbelt in which recent work (e.g. Burbank & Beck 1989) has placed tight constraints on the chronology of its development and in which seismic reflection, drillhole, stratigraphic and surface mapping data are available.

The Salt Range and Potwar Plateau are located southwest of the northwestern syntaxis of the Himalayas. The advance of deformation far into the foreland in this area has been attributed by many workers to the presence of the Salt Range Formation evaporites as a weak detachment horizon (e.g. Sarwar & De Jong 1979, Seeber *et al.* 1981, Lillie *et al.* 1987, Butler *et al.* 1987). The narrow cross-sectional taper in the Potwar Plateau (from less than 1° to about 3°) can also be attributed to these evaporites, which are predominantly salt. Laboratory measurements (e.g. Carter & Hansen 1983, Chester 1988) indicate that salt is ductile at typical geologic strain rates except in the top few hundred meters below the surface. At depths of only a few km it can be between one and two orders of magnitude weaker than most other rocks.

The large strength contrast between moderately strong rocks and salt means that a wedge can maintain a much narrower taper than would otherwise be possible (as little as 1° or less, as opposed to typical values in the range of 6–12° in foldbelts with stronger coupling) (e.g. Chapple 1978, Davis *et al.* 1983). The limited coupling in salt also means that the maximum principal stress axis must be nearly horizontal, so that there should be no strong preference in vergence direction (Fig. 3b) (Davis & Engelder 1985).

Above the Salt Range Formation are lower Cambrian clastic rocks (non-marine and shallow marine). Unconformably above them are Permian and Mesozoic rocks, including some highly competent sandstones and carbonates. Paleocene and lower Eocene rocks, largely shallow marine carbonates, are followed by an unconformity and the incompetent molasse of the Neogene Rawalpindi and Siawalik Groups (Gee 1989). In the southern Potwar Plateau and Salt Range, the total thickness of the competent section (Cambrian to Eocene) is only about 600 m, while the incompetent Eocambrian and Neogene sections are thicker (about 0.5–2 km and 1–5 km, respectively). Thus, the mechanical situation can be thought of as one in which there is a

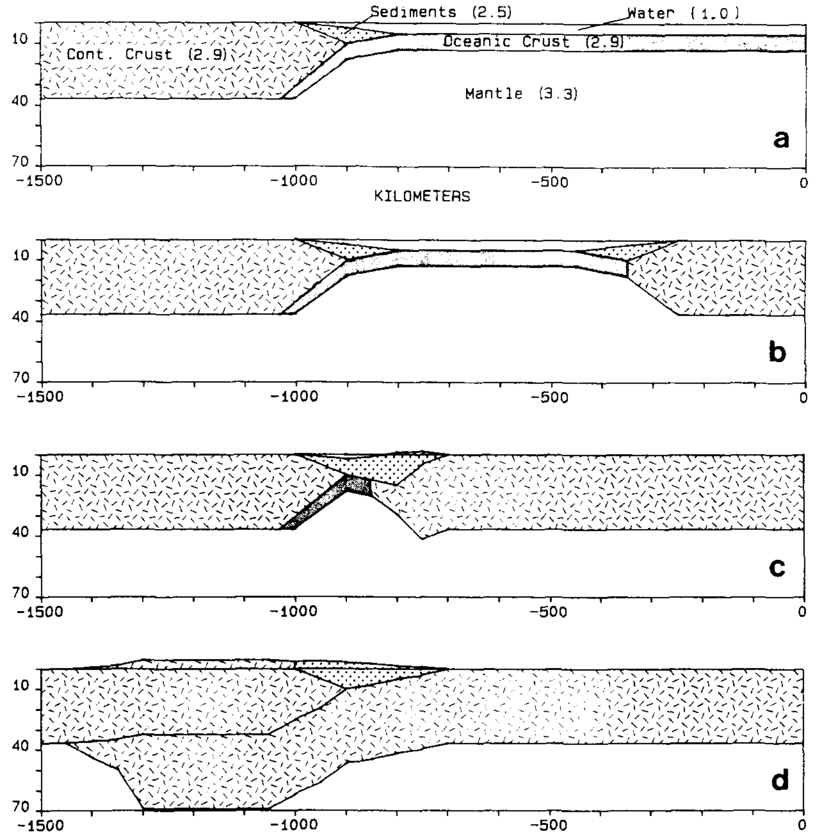

Fig. 5. Two-dimensional density models for stages of ocean basin closure and continent–continent collision. The sections retain a state of Airy isostatic equilibrium at their bases (70 km), for the thicknesses and densities (in g cm^{-3}) shown for crust, mantle, sediments and water. Models have vertical exaggerations of 4:1. (a) Convergent continental margin with oceanic crust subducting. (b) 550 km before continental crusts collide. (c) 50 km before continental crusts collide. (d) 500 km of continental underthrusting following collision. Although the width of ocean crust consumed is unknown, the thrust belts discussed in this paper are at the general states of crustal structure and sedimentary thicknesses depicted in (a) & (b) for the Makran accretionary wedge, (c) for the Sulaiman thrust lobe and (d) for the Salt Range–Potwar Plateau and Kashmir thrust belts. Modified from Lillie (in press).

rigid 'beam' (Cambrian to Eocene) sandwiched between two weak zones, the lower of which is ductile; the entire system is in turn underlain by an essentially unyielding crystalline basement.

Seismic reflection lines indicate that a considerable amount of internal shortening has been accommodated in the eastern (Fig. 6b) as compared to the central and western (Fig. 6c) Potwar Plateau. Jaumé & Lillie (1988) attribute this contrast in deformation to differences in basement dip, with the central and western Potwar (unlike the eastern) having a basement dip enough to obviate the need for a substantial build up of topographic slope. Thinning of the salt towards the east is another factor that would tend to build the topographic slope there (Butler *et at.* 1987). However, the applicable power-law exponent for salt is quite large, probably near 5 (e.g. Carter & Hansen 1983, Chester 1988), so the shear stress is only very weakly dependent upon strain rate. Thus, the shear traction along the base of the foldbelt should not increase greatly unless the salt becomes extremely thin or if it 'pinches out' locally. Pennock *et al.* (1989) point out that although reconstruction yields an *average* salt thickness of roughly 500 m in the eastern Potwar (Fig. 6b), the thickness appears to approach zero beneath some synclines (see Johnson *et al.* 1986). The mobility and buoyancy of salt tend to cause salt to flow into anticlines, with corresponding synclinal pinch-out (asperity) zones. Finite element modeling (Moussouris 1990) suggests that even relatively small local 'asperities' without salt at the base of the overthrust belt might become local, highly coupled zones capable of influencing the generation of structures within the foldbelt. The sticking of the thrust wedge at salt-free asperities in the eastern Potwar Plateau might help to explain the counterclockwise rotation of the Salt Range and Potwar Plateau that has been observed paleomagnetically (e.g. Opdyke *et al.* 1982).

Timing and mechanics of Salt Range and Potwar Plateau deformation

The Salt Range rises abruptly above the Jhelum River plain, overriding its own depositional fan and exposing the entire sedimentary section down to and including the evaporites (Fig. 6c). Extending about 100 km north of the Salt Range is an elevated, nearly flat region, the Potwar Plateau, occupying a position analogous to that of the Molasse Basin between the Jura mountains and the Alps. There is very little indication of internal shortening in the southern part of the western and central Potwar Plateau, where most of the advance of

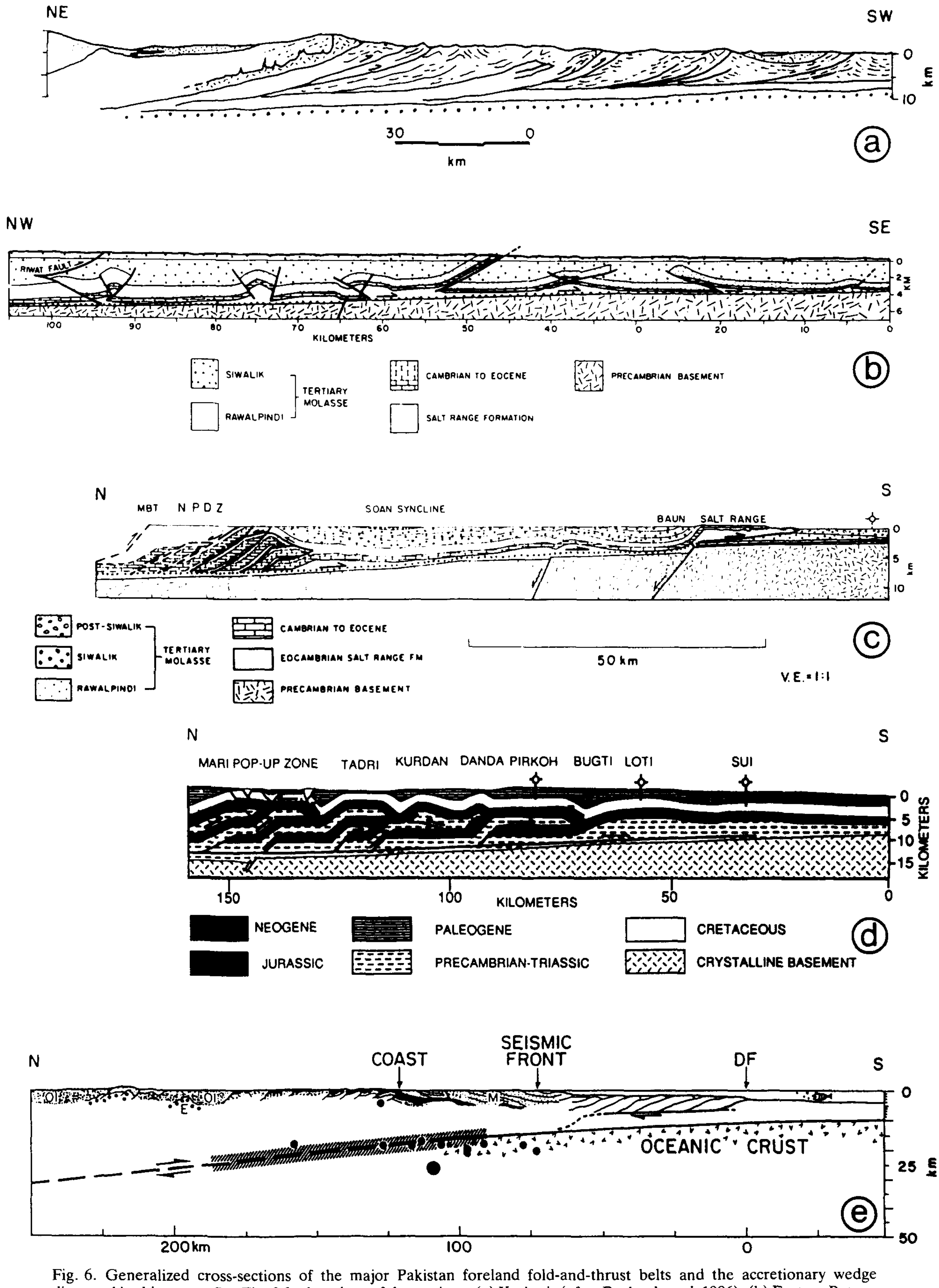

Fig. 6. Generalized cross-sections of the major Pakistan foreland fold-and-thrust belts and the accretionary wedge discussed in this paper. See Fig. 2 for locations of the sections. (a) Kashmir (after Burbank *et al.* 1986). (b) Eastern Potwar Plateau (after Pennock *et al.* 1989). (c) Central Salt Range–Potwar Plateau (after Baker *et al.* 1988). NPDZ = Northern Pakistan deformed zone; MBT = Main Boundary Thrust. (d) Sulaiman Range (after Jadoon 1991, Jadoon *et al.* 1992). (e) Eastern Makran accretionary wedge (after Byrne *et al.* 1992). DF = Deformation Front.

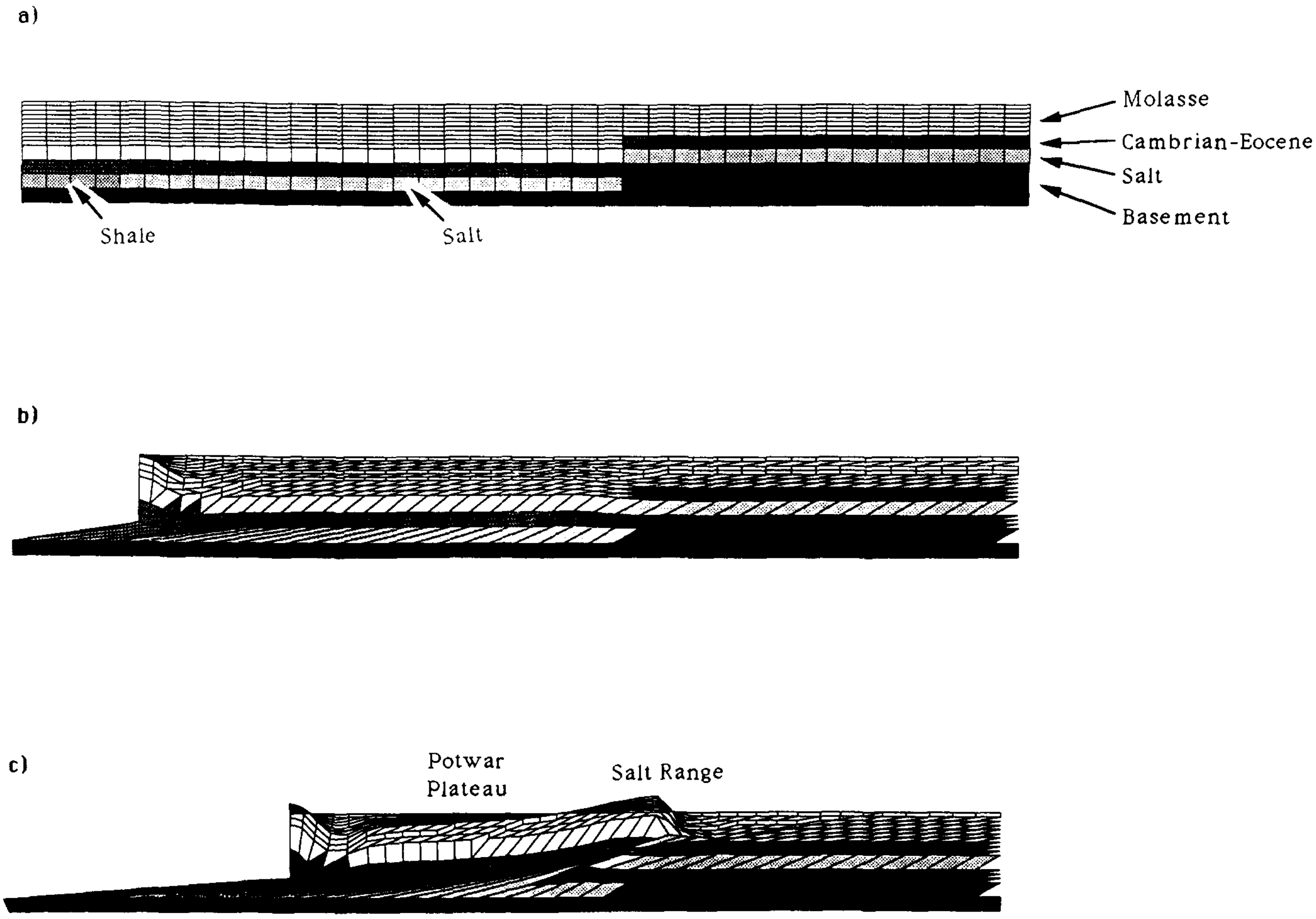

Fig. 7. Finite element model for the central Salt Range–Potwar Plateau (after Moussouris 1990). Vertical exaggeration is about 3:1 and deformations are further exaggerated by a factor of 3:1. (a) Starting case, with north to the left. Shading and labels indicate the different rock types. Basement rocks are covered by salt, the strong Cambrian to Eocene section, and finally molasse, the thickness of which has relatively little effect upon the modeling. Note the basement offset in the foreland. (b) Initial movement is impeded by the buttress effect of the basement offset, so that the salt layer thickens and 'hydraulically' uplifts the Potwar Plateau in the south (at right). (c) Once the Salt Range Thrust is 'lubricated' by salt, the deformation front begins to advance southward.

the thrust wedge appears to have been accommodated along the Salt Range Thrust (e.g. Lillie *et al.* 1987).

Moussouris (1990) generated a highly simplified finite element model for deformation in a weak-basal foldbelt with basement relief, using software developed by Richardson (1978). The starting case (Fig. 7a) assumes an initial rectangular geometry and four different materials; basement (very strong), Eocambrian salt (weak), the Cambrian-to-Eocene section (strong), and young molasse (weak). Note that a break in the level of basement offsets the layers; this break simulates a down-to-the-north normal fault observed on seismic profiles to underlay the Salt Range (Baker *et al.* 1988). Even this simple model can reproduce several aspects of the tectonics of the Salt Range–Potwar Plateau foldbelt (Figs. 7b & c). Initially, the region to the north of the basement offset is elevated into a high plain, like the Potwar Plateau. Next, southward towards the foreland there develops a more highly elevated zone with considerable relief on its right (south) side, bordered farther to the south by an undeformed zone analogous to the Jhelum Plain. The elevated area, which is located above the basement offset, results from slip due to the local stress concentration caused by the basement relief and is analogous to the uplift associated with the initial slip along the Salt Range Thrust reported by Burbank & Beck (1989). Within most of the Potwar Plateau, the model predicts that the weak basal traction causes the maximum principal stress axis to be close to horizontal. As noted earlier, this should result in relatively symmetric structures without a strongly preferred vergence direction, like that observed in the eastern Potwar Plateau (Fig. 6b). Only if weak salt is somehow introduced along the thrust ramp itself is there significant southward movement along it.

Lillie *et al.* (1987) show seismic reflection data that indicate basement relief in the form of a down-to-the-north fault beneath the ramp of the Salt Range Thrust. They suggest that this relief is the result of a flexural normal fault that predates that advance of thin-skinned thrusting into that area. Because the roughly 1 km throw of the normal fault exceeds the local thickness of the evaporites, the salt-lubricated translation of the allochthonous Potwar Plateau is interrupted at the fault. Photoelastic modeling by Wiltschko & Eastman (1983) and a finite element study by Schedl & Wiltschko (1987) showed that angular offsets in basement can cause the generation of stress concentrations that trigger thrust ramping, including some that may reach all of the way to the surface. Moussouris (1990) obtains a very similar result even when the weakness of the salt on the upthrown (south) side of the normal fault is taken into account.

To the first order, the Salt Range–Potwar Plateau thrust wedge has undergone a generally forward (southward) progression of deformation. However, Burbank (1983), Burbank & Raynolds (1988) and Burbank & Beck (1989) have identified significant 'out-of-sequence' thrusting. They report that at least 4 km of shortening happened in the Salt Range from about 5 to 4.5 Ma, well before the end of the major deformation in the northern Potwar Plateau. This was followed, after a hiatus of about 3 Ma, by renewed slip of at least 12 km, contemporaneous with shortening along structures at the far eastern end of the Salt Range. We suggest that the temporary pause in uplift in the Salt Range from around 4.5 to 2 Ma resulted from the local doubling of the strong Cambrian-to-Eocene section along the thrust. In this way, the initial uplift in the Salt Range may have served to strengthen that part of the foldbelt with the greatest degree of local stress concentration. Lacking the lubricating effect of the salt in its up-dip regions, the thrust ramp must initially have been much stronger than it is today, when large volumes of salt fill the fault zone (Fig. 6c). This lack of weakening, combined with the strengthening effect of the build up of topography may explain why shortening in the foldbelt did not continue to be concentrated in the region of the basement fault. Instead, the primary locus of shortening returned to the northern Potwar Plateau at about 4.5 Ma (Burbank & Beck 1989).

We suggest that as deformation continued in the northern Potwar Plateau, salt migrated southward beneath the southern Potwar Plateau (Gee 1983) over the basement normal fault buttress, driven by the gradient in overburden. In effect, the nearly 3 million year hiatus in thrusting in the Salt Range may simply be the amount of time it took the viscous Eocambrian salt to be injected far enough up the Salt Range Thrust ramp to lubricate the otherwise hard-to-move part of the fault within the strong Cambrian-to-Eocene section. The likely mechanism for this motion is the hydrostatic pressure gradient resulting from the increasing depth and overburden northward along the décollement. Having migrated up the fault zone, the salt would then have made large-scale thrusting energetically feasible.

If the salt advanced as though it were an extremely viscous magma being injected into a dyke (in this case the Salt Range Thrust) then it would have been driven by a pressure gradient of about 1 kPa m^{-1}. This flow would then be replenished by southward flow of salt beneath the southern Potwar Plateau. The replenishing flow beneath the Potwar Plateau was driven by pressure gradients about an order of magnitude smaller, due to the shallow dip of the salt layer beneath the plateau. Thus, the rate of salt injection up the Salt Range Thrust must ultimately have been limited by how quickly salt could migrate southward beneath the Potwar Plateau, assuming that the initial, abortive slip on the Salt Range Thrust at about 5 Ma provided a geometry in the fault zone that was suitable for the initiation of the injection of salt up the fault zone ramp. Given the viscosity of salt at such low temperatures, on the order of 10^{18}–10^{19} Pa s^{-1}, the migration of the salt should have taken a few million years, providing a possible explanation for the 3 million year hiatus in slip along the Salt Range Thrust (Moussouris 1990).

SULAIMAN FOLDBELT

The Sulaiman foldbelt is part of the obliquely convergent margin at the western edge of the Indian plate (Figs. 1 and 2), which is moving northward with respect to Asia at about 4 cm $year^{-1}$ (Minster & Jordan 1978). One remarkable aspect of the festoon-shaped Sulaiman lobe is that it includes both E–W-striking thrusts at its southern boundary and N–S-striking thrusts at its eastern edge (Fig. 2), although convergence at the eastern front must have a very large oblique component. The rocks exposed at the front of the Sulaiman Range, facing east, and the Sulaiman lobe front, facing south, are all Tertiary in age. The sedimentary section in those areas is extremely thick; seismic reflection lines show that Precambrian basement is at least 10 km deep at the deformation front (Banks & Warburton 1986, Humayon *et al.* 1991, Jadoon *et al.* 1992). Behind the deformation front, the section is expected to be considerably thicker than that, based on cross-section balancing (Banks & Warburton 1986, Jadoon *et al.* 1992) and gravity modeling (Khurshid 1991). A likely explanation for this thick sedimentary pile is that it represents a northern continuation of the Mesozoic rifted margin sequence on the western edge of the Indian subcontinent (Humayon *et al.* 1991).

The great breadth of the zone of foreland thrusting and accommodation structures along the lateral flanks in the Sulaiman region might be expected to be related to the presence of an extremely weak detachment in salt. However, there is no evidence for evaporites beneath the Sulaiman foldbelt; the nearest documented occurrence of evaporites is 200 km east of the deformation front (Humayon *et al.* 1991). Given the apparently narrow cross-sectional taper of this foldbelt, it is hard to understand how it can be as much as 200 km wide, with 76 km of shortening in the frontal 129 km (Jadoon *et al.* 1992), unless there is a weak detachment layer somewhere at depth. Furthermore, the mean topography (Jaumé 1987, Jadoon *et al.* 1992), steep in the first few tens of kilometers from the deformation front, flattens out towards the interior (Fig. 4d) in a manner compatible with a down-dip transition to a weak detachment (Davis *et al.* 1983). This suggests that some of the lower part of the thick sedimentary section within the foldbelt deforms in a ductile manner at relatively low shear stress; however, we suggest that the weak zone is not necessarily in evaporites. An additional factor likely to cause the front to be relatively elevated is the effect of isostasy in overthrusting an ocean–continent boundary. The front of the foldbelt, having reached the thicker and hence more buoyant continental crust, may simply be elevated isostatically, in contrast to the rearward portion of the wedge that remains over oceanic basement (Fig. 5c).

The propagation of deformation so far into the foreland without a large cross-sectional taper may be realistic if rocks deep in the section can shorten by a mechanism that operates at shear stresses well below the stress levels required in the overlying, friction-dominated rocks. Unlike the Salt Range, where the limestone-rich Cambrian-through-Eocene section is only 1 km thick, it is over 7 km thick beneath the deformation front of the Sulaiman wedge, and thickens to the north and west (Humayon *et al.* 1991, Jadoon *et al.* 1992). Although they remain brittle to much greater depths than evaporites, fine-grained limestones can undergo significant non-brittle strain at temperatures considerably lower than many other rocks. The shortening would be roughly subhorizontal and its magnitude would decrease with larger grain sizes and with lower temperatures at shallower depths.

Although time-dependent mechanisms are probably less important than friction in foldbelts that are undergoing rapid shortening at shallow depths, they may be significant in many other cases. For example, when strain rates, temperatures, lithologies and grain sizes favor pressure solution, that mechanism may play an important role in the strain history of a foldbelt (e.g. Engelder & Geiser 1979). In order for a 100 m thick section to accommodate 3 cm year^{-1} of slip, strain rates of only 10^{-12} s^{-1} are required. Thicker sections could accommodate the slip with proportionally lower strain rates. In a sufficiently thick stratigraphic section with enough fine-grained limestones, it is quite feasible for pressure solution to accommodate the necessary strain rates. Extrapolation of published laboratory data (e.g. Rutter 1976, 1983, McClay 1977) suggests that with temperatures of 200–250°C, shear stresses on the order of only 1 MPa may lead to pressure solution in fine-grained, calcite-rich rocks at the required strain rates. A temperature of 200–250°C at the bottom of the Sulaiman wedge ($\simeq$15–20 km deep) corresponds to a mean thermal gradient of only about 10–15°C km^{-1}. Vitrinite reflectance data from nearby wells are reported to be consistent with moderately high thermal gradients (H. Jorgen personal communication, 1989). Data from wells 1.8–4.7 km deep, located mostly in frontal regions of the foldbelt (Khan & Raza 1986, Raza *et al.* 1989), yield geothermal gradients of 24–34°C. Thermal gradients probably do not remain quite so high farther from the front and at greater depth. However, given published flow laws for carbonate rocks (e.g. Schmid *et al.* 1977, 1980), it is even possible that some intragranular creep (in addition to large-scale pressure solution) occurs in some deeper parts of this foldbelt. Deformation by a variety of ductile mechanisms has been recognized observationally in the deeper rocks of the foldbelts for some time now (e.g. Schmid 1975).

The back of the Sulaiman foldbelt is characterized by sediments that are very deep (up to 20 km) because of their genesis as part of the thick Mesozoic rifted margin prism and subsequent thickening by thrusting (Fig. 5c). In contrast, sediments at the extreme front of this mountain range, including recently deposited molasse, are about 10 km thick. Hence, the front of the Sulaiman wedge is much less likely than the deep rearward portions of the foldbelt to show shortening by low-stress, time-dependent mechanisms such as pressure solution. The very steep topographic slope at both the eastern and southern fronts of Sulaiman lobe (Fig. 4d), manifested as a culmination wall of a passive roof thrust (Fig. 6d), supports the idea that basal friction is high where the detachment zone is shallower (Humayon *et al.* 1991, Jadoon *et al.* 1992).

Ideally, one would like to obtain samples of carbonates that have been buried to depths of 15 km or so in the Sulaiman wedge in order to determine whether or not they show any signs of distributed, non-frictional deformation. Unfortunately, such rocks do not appear to be exposed at the surface. Unlike rocks that typically provide good zones of detachment, such as shales, carbonates are expected to be weak only when warm and deep. Thus, any deep décollement in Triassic carbonates would not bring the carbonates and rocks directly above them to the surface. Instead, at moderate depths where the carbonates are no longer weak, detachment should step up into shales higher in the section that are weak regardless of temperature; this appears to be happening in the passive roof duplex observed along the Sulaiman front (Banks & Warburton 1986, Humayon *et al.* 1991, Jadoon *et al.* 1992). The overall taper of the Sulaiman wedge is only about 3° (Jadoon *et al.* 1992), sufficiently small so as to suggest the presence of a weak zone of detachment. Although deformation in the upper half of the crust is probably governed primarily by the frictional strength of rocks, our working hypothesis is that the relatively subdued character of the profile in Figs. 4(d) and 6(d) results from this not being true of any of the rearward portions of the Sulaiman wedge. Instead, much of the strain at depth may be accommodated by weaker, perhaps macroscopically ductile mechanisms.

Frictional behavior is not necessarily seismic in character (e.g. Scholz 1988), but macroscopically ductile behavior is unlikely to accumulate sufficient elastic strain to permit the generation of significant seismicity. The assumption of ductile behavior in the back of the Sulaiman wedge leads to the prediction that detachment-related seismic events would be lacking there. Teleseismically determined earthquake locations contain considerable uncertainties in location, but the data do seem to indicate that relatively few earthquakes occur between the frontal portion of the Sulaiman lobe and the highly seismic Chaman transform fault zone. These data are at least consistent with the hypothesis that most slip along the base of the rearward (but not the frontal) parts of the Sulaiman occurs in a ductile and aseismic manner. This contrasts sharply with both the overall aseismicity of the Salt Range, which is probably due to the ductility of salt all the way to the deformation front (Seeber & Armbruster 1979), and the distribution of seismicity at the base of the Makran wedge, which is confined to the deeper regions 75 km or more from the deformation front (Byrne *et al.* 1992). The apparent seismic activity in the frontal regions of the Sulaiman wedge is superficially similar to that described by Seeber *et al.* (1981) for the central Himalayas. However, in the latter case the seismicity appears to extend downdip beneath all of the thin-skinned wedge, as opposed to being mostly limited to the frontal regions of the Sulaiman.

The overthrust wedge of Sulaiman should remain well coupled to the basement wherever the basal décollement is in strong, frictional rocks. Weaker coupling is expected along the base of the wedge where the décollement is deeper. This leads to the expectation that strong mechanical coupling should cause the frontal part of the eastern Sulaiman wedge to be dragged northward with respect to the rest of the wedge, causing the eastern Sulaiman to translate northward along the left-lateral Kingri Fault (Fig. 2). The basal décollement in the area of the Kingri Fault is somewhat over 14 km deep (Humayon *et al.* 1991). Thus, although the data are at present insufficient to draw strong conclusions, the available data are consistent with the idea that the parts of the Sulaiman wedge with a detachment deeper than roughly 12–15 km slide in a largely ductile manner, perhaps over warm and weak carbonates.

THE MAKRAN ACCRETIONARY WEDGE

The Makran margin of southwestern Pakistan and southeastern Iran (Fig. 2) is a zone in which northward subduction of neo-Tethyan crust has been taking place since the Early Cretaceous (Şengör *et al.* 1988). Located to the west of the Chaman fault zone, the Makran is not strictly part of the same India–Asia collision as are the other three thin-skinned wedges discussed here. Rather, it currently constitutes the boundary between the Eurasian and Arabian plates (Fig. 1). The Makran is bounded on the west by the Oman line, a zone of major strike-slip motion to the west of which is the salt-dominated Zagros mountain belt.

Located to the north of the Makran forearc are two major accreted terranes (Fig. 2). Much of Afghanistan consists of the Afghan, or Helmand block, and to the north the Turan block; farther to the west, in eastern Iran, is the Lut block. These blocks are Gondwanan in origin and are thought to have docked with Asia after the subduction of a large amount of Paleotethys ocean crust to their north during the Mesozoic (Tirrul *et al.* 1983, Şengör *et al.* 1988).

The Kandahar Arc, south of the Lut and Afghan blocks, is associated with convergence at the Makran margin since the Late Cretaceous. During that time, an exceptionally wide (500 km) forearc has formed. South of the volcanic arc is Late Cretaceous to Paleogene flysch belt in the Ras Koh Range that probably includes the earliest sediments to be accreted at that margin, the Mashkel forearc basin, located in the Baluchistan desert, and the Makran accretionary wedge itself (Farah *et al.* 1984, Leggett & Platt 1984). The subaerial portion of the wedge is divided into three relatively distinct deformational zones: the Northern, Central and the Coastal Makran Ranges. These zones young toward the trench (southward), ranging in age from Paleogene to Miocene (Harms *et al.* 1984, Leggett & Platt 1984).

Of the total 300 km width of the accretionary wedge, 200 km is exposed subaerially. This contrasts sharply with most accretionary wedges, which are typically exposed only discontinuously in isolated islands along the outer-arc high, such as Nias, Barbados and Kodiak. The massive size and exposure of the Makran wedge is probably closely related to its very large sediment supply. The sediment package at the deformation front is 5–7 km thick. Of this, roughly half is accreted at the front into a series of evenly spaced folds and imbricate thrusts (White 1979). Field relations and mass balance arguments both strongly suggest that most of the remainder of the sediments, underthrust at the front, are underplated farther to the north (White 1979, Platt *et al.* 1985).

The overall taper of the Makran accretionary wedge is about 4°, with a value somewhat greater offshore and less onshore. Critical taper arguments indicate that narrow tapers result when pore fluid pressures are high, particularly if the elevation of fluid pressures is most pronounced in the zone of basal detachment. Davis *et al.* (1983) suggest that the taper implies fluid pressure values within a few percent lithostatic. Platt (1990) suggests that superlithostatic pore pressures may exist and that tensile fracturing may be an important process in the Makran wedge. Speculations about overpressures are supported by the presence of mud volcanoes along the coast (Snead 1964, Ahmed 1969). The undercompacted, relatively porous state of overpressured sediments also means that the transition from loose, unlithified sediment to hard rock is likely to occur deeper in the Makran wedge than in subaerial wedges, such as the Kashmir Himalaya.

One important implication of this transition is its effect upon seismicity. There is no simple one-to-one relationship between brittle and seismically capable behavior, but Zhang *et al.* (1989, 1993) have shown for clastic rocks that the transition from non-localized, non-dilatant slip to discrete, dilatant slip depends upon both effective confining pressure and porosity. At high porosities, the overall behavior is brittle–frictional, but slip does not occur in a manner conducive to seismicity. The ability of frictional rocks to support seismic slip has been described in terms of the relative magnitudes of dynamic and static friction coefficients (e.g. Rice & Ruina 1983). This explains quite nicely the lack of earthquakes nucleating in the top few km in many fault zones (e.g. Meissner & Strehlau 1982). Byrne *et al.* (1988) explain the aseismicity of accretionary wedges in much the same way, except that undercompaction in accretionary wedges means that the aseismic zone above the transition to stick–slip behavior and the release of elastic strain in earthquakes is much deeper, typically about 15 km.

Byrne *et al.* (1992) have examined the seismic record of the Makran margin and conclude that aseismic conditions exist from the deformation front northward about 75 km, to a point about 15 km deep, roughly beneath the shoreline (Fig. 6e). The plate boundary in eastern Makran ruptures in great thrust earthquakes, including a magnitude 8.1 event in 1945. Because of the lack of large events that are clearly recorded either instrumentally or historically, it is not clear whether or not western Makran undergoes great thrust earthquakes. The location of the deep end of the seismogenic zone for plate-boundary events at this and other subduction zones is apparently determined by the much deeper, thermally-controlled transition to intragranular creep. Thus, the 15–50 km deep zone of basal thrusting earthquakes in eastern Makran contrasts markedly with the Sulaiman wedge, where most events are located where the base of the wedge is shallow.

The Makran margin and its accretionary wedge have had a long and complex history. However, the anomalous width and moderately narrow cross-sectional taper of the wedge are understandable in terms of the large sediment supply and the resulting overpressures. The undercompaction within the wedge due to overpressuring explains the aseismicity of its frontal 75 km, where the base of the wedge is within 15 km of the surface. Ultimately, it is the fact that the crust beneath the Makran is oceanic, and subducting, that explains its lack of buoyancy and its attendant ability to support large quantities of clastic sediments without most of it eroding away (Figs. 5a & b). The great breadth, narrow taper, and frontal aseismicity result, in turn, from the hydrologic implications of that massive sediment supply.

COMPARISONS AND SUMMARY

We have surveyed, in varying degrees of brevity, the tectonics of four major thin-skinned contractional wedges in Pakistan. All are part of the closure of ocean and eventual continental collision along the southern margin of Asia. However, they are at very different stages of this process (e.g. Fig. 5). In each case, the width and taper of the region of thin-skinned thrusting can be related to the surmised strength of the zone of detachment, based upon the likely lithology and temperatures of the strata there (Fig. 8).

In Makran, oceanic crust is still being subducted (Figs. 5a & b), and a huge supply of clastic sediments is being accreted and underplated, probably in an undercompacted and overpressured state. This has led to the formation of a wide but fairly thinly tapered wedge that is aseismic in its frontal 75 km (Fig. 6e).

The Sulaiman wedge is undergoing active collision; gravity data suggest that the zone of transition from oceanic to continental crust is just now being underthrust (Fig. 5c). Isostatic compensation by shallow mantle material allows the extremely thick continental margin sequence to be preserved. The section is highly deformed at the front, but the narrowed wedge taper and apparently reduced seismicity to the north and west suggest the large-scale occurrence of some sort of thermally-activated ductility (perhaps pressure solution) in fine-grained carbonates of the passive margin sequence (Fig. 6d). If so, then the décollement mechanics of the Sulaiman are quite distinctive (Fig. 8).

In northern Pakistan, collision has progressed until the lower thrust plate includes full-thickness crust of the craton (Fig. 5d). As a consequence of isostasy, the sedimentary section in the Salt Range–Potwar Plateau foldbelt and in Kashmir is therefore much thinner than it is in the Makran and Sulaiman regions. However, the Salt Range–Potwar Plateau foldbelt behaves quite differently than the Kashmir Himalaya because its thin sediments include an evaporite horizon which is ductile even at quite shallow depths.

The tectonics of the Salt Range–Potwar Plateau foldbelt are dominated by the presence of the Eocambrian salt at the base of the sedimentary column and by a major normal fault in the basement. The salt allows the

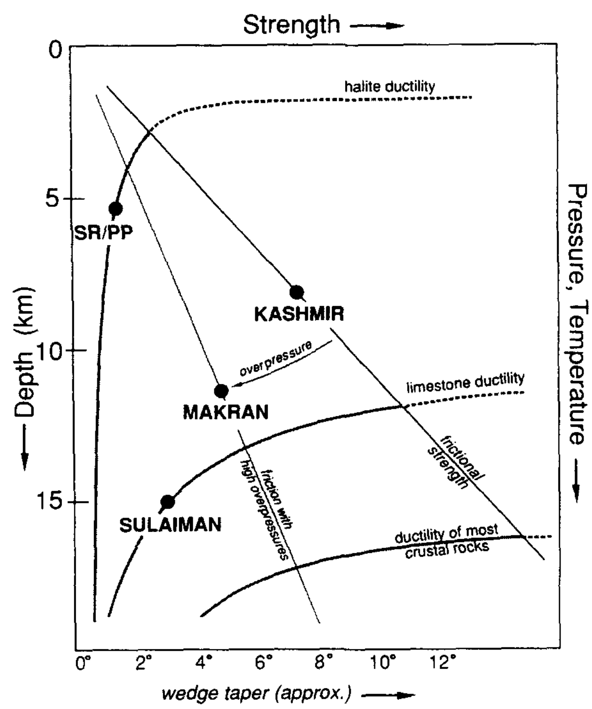

Fig. 8. Schematic illustration of the major thin-skinned contractional wedges of Pakistan in terms of the pressure and temperature in the zone of basal detachment (vertical axis) and the strength of coupling there (horizontal axis). The straight lines represent the confining-pressure-dependent frictional strength of crustal rocks, which increases with depth. With elevated pore fluid pressures (as in Makran), frictional strengths increase more slowly with depth. The shaded curves represent ductile strengths, which decrease with increasing temperature. The ductile strength curves are dashed at depths shallower than the brittle–ductile transition, where friction is weaker and is the dominant deformation mechanism. Stronger coupling along the basal thrust requires larger wedge tapers. The Kashmir Himalaya is governed by strong friction, but the Salt Range–Potwar, Sulaiman and Makran wedges are weak due (respectively) to low-temperature ductility in salt; moderate temperature weakness of carbonates beneath a thick sedimentary pile; and elevated pore-fluid pressures that greatly reduce effective pressure.

overall wedge taper to be extremely narrow (Fig. 8), permits the southern Potwar Plateau to be translated southward with very little internal deformation (Fig. 6c), and causes deformation to occur on backward- as well as forward-vergent structures (Fig. 6b). There is a large offset in basement at the front of the central and western portions of the Potwar Plateau, resulting from the presence of a flexural normal fault. This offset apparently acted as a stress concentrator and triggered the ramping to the surface of the Salt Range Thrust, exposing the entire section from the Eocambrian upward (Fig. 6c). The timing of subsequent motion on the Salt Range Thrust may be closely related to the migration of fault-weakening salt up the thrust ramp (Fig. 7).

In the Kashmir Himalaya, the collision is seen at its most mature state (Fig. 5d). The sedimentary pile being accreted, other than molassic material derived from the Himalayas themselves, is relatively thin (Fig. 6a). Because of the lack of evaporites in this area, the sediments provide no unusually weak décollement horizon (Fig. 8). Thus, the foreland fold-and-thrust belt is highly deformed, with predominantly forward-vergent structures. It is a relatively narrow belt, with a cross-sectional taper that is much larger than those of the other major mountain belts of Pakistan.

Our brief survey of the four major zones of thin-skinned orogenic deformation in Pakistan indicates that, despite similarities in setting and convergence rate, these belts differ in important ways. We find that many of these differences are explicable in terms of the different thicknesses and lithologies of the sedimentary piles that the wedges encounter at their deformation fronts. These differences are related not only to the various paleodepositional environments, but, equally as important, to the various stages in the collisional process represented by each belt.

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