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'Passive-roof' duplex geometry in the frontal structures of the Kirthar and Sulaiman mountain belts, Pakistan

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Abstract—Exploration for hydrocarbons over the past few years has greatly improved our understanding of the geometry of frontal mountain belt structures. In this study we introduce and discuss the concept of the 'Passive-roof duplex', using as the main example the Kirthar and Sulaiman Ranges in the Baluchistan Province of Pakistan. Structures similar to those described here have been recognized previously in other mountain belts, and they appear to exist as a common feature in many more frontal regions of mountain belts. Our example of a Passive-roof duplex which we describe from Pakistan is compared briefly with similar structures reported by others.

The *Passive-roof duplex* is here defined as a duplex whose roof thrust has backthrust sense (*Passive-roof thrust*) and whose *roof sequence* (those rocks lying above the roof thrust) remains relatively 'stationary' during foreland directed piggy-back style propagation of horses within the duplex.

GEOLOGICAL SETTING OF THE KIRTHAR AND SULAIMAN THRUST BELTS

FIGURE 1 shows the geographical and tectonic setting of the Kirthar and Sulaiman thrust belts. The thrust belts of western and north-western Pakistan were initiated during the collision of the Indian and Eurasian plates throughout the Tertiary. The details of plate configuration and motion are omitted from this study and the reader is referred to several publications (Molnar & Tapponier 1975, Bordet 1978, Acharyya 1979, Bingham & Klootwijk 1980). A major contribution to understanding of the geology of Pakistan was provided by a substantial report and maps published by the Hunting Survey Corporation in 1960. A collection of twenty four papers compiled by the Geological Survey of Pakistan (1979) also provides a broad overview of the geodynamics of Pakistan.

The Kirthar thrust belt and the structures within it strike approximately N–S and are bounded to the west by a zone of steep to vertical left lateral transcurrent faults, named the Chaman Fault Zone (Lawrence & Yeats 1979, Lawrence *et al.* 1981). The relationship between the westerly dipping thrust surfaces of the Kirthar thrust belt and the steep Chaman faults is poorly understood.

The Sulaiman Range forms a continuation of the Kirthar Range around the tight arc of the Sibi Trough. Like the Kirthar thrust belt, the Sulaiman Range is formed from imbricate slices which here developed during southerly propagating piggy-back thrusting. Figure 2 shows a geological map, and Fig. 3 a simplified stratigraphic column for the Kirthar and Sulaiman Ranges. Rocks exposed at the surface, which are involved in thrusting, range in age from Carboniferous to Recent, although older rocks may be involved at depth. The most likely major detachment horizons are indicated in Fig. 3.

The Sibi Trough (Figs. 1 and 2) is a molasse basin which developed as a foredeep ahead of the developing Kirthar and Sulaiman thrust complexes in Miocene to Recent time, with the accumulation of at least 7000 m of sediment. In the region between Quetta and Sibi the molasse basin is tightly constricted and structures are extremely complex. It is in this area that the molasse sediments are affected by structures which propagated eastward and southward and which, in Fig. 2, display obvious interference patterns. The majority of coarse clastic sediment supplied to the Sibi Trough was locally derived from the uplifting mountain belts, and has been continuously reworked during development of the thrust belts. A similar relationship between tectonics and sedimentation has been detailed for the Siwalik molasse basin further north along the southern margin of the Himalaya and Hindu Kush (Burbank & Reynolds 1984).

Duplex geometry

Figures 4 and 5 show two vertical cross-sections, one WNW–ESE across the Kirthar thrust belt in the vicinity of the Bolan Pass, and one N–S across the Sulaiman Range. The lines of section are shown in Figs. 1 and 2. The structure to the east of the Bolan Pass and external part of the Sulaiman Range is supported in part by fair to good quality seismic reflection data, but the overall interpretation is based mostly on field and airphoto/ Landsat image mapping. In the Sulaiman Ranges (Fig. 5) the floor thrust is suspected to be within a sequence of evaporites of Eo-Cambrian age. The roof thrust is within the Lower Eocene Ghazij Formation shales in most of the range but appears to be in Lower Cretaceous Goru Formation shales in the northernmost horses of the duplex. All of these units are relatively incompetent and the roof and floor thrusts are separated by a thick sequence (up to 8 km) composed dominantly of Jurassic, and in the south also, Palaeocene limestones.

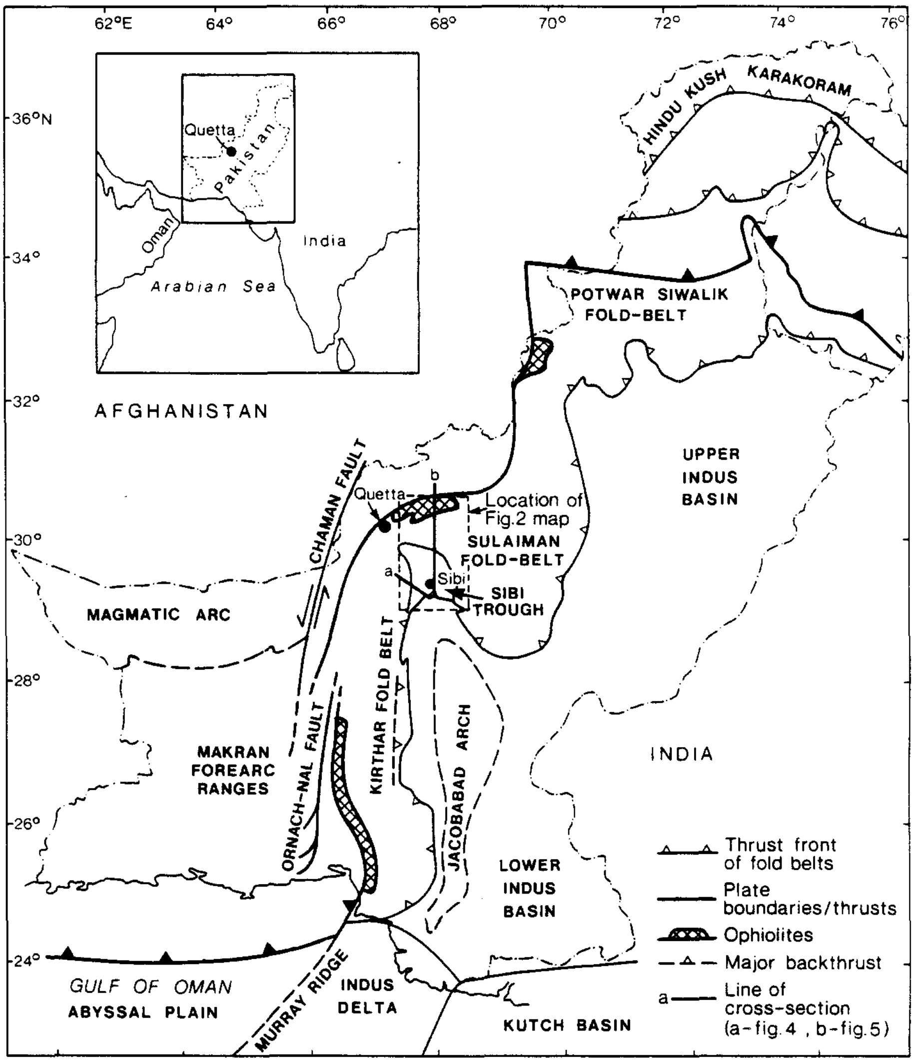

Fig. 1. Geographic and tectonic setting of the Kirthar and Sulaiman Ranges, with the locations of two cross-section lines for Figs. 4 and 5.

In the Bolan Pass area of the Kirthar Range (Figs. 2 and 4) there is a distinct difference in the style of folding above and below the Ghazij Formation. Below the Ghazij Formation, folds involving the thick limestone sequence are generally open, whilst above, they are commonly close to tight and occasionally isoclinal and strongly asymmetric. This demonstrates some detachment within the Ghazij Formation. By analogy with the Sulaiman Range it is likely that the regional sole thrust in the Kirthar Range is within Eo-Cambrian evaporite or equivalent section. However, as yet there are no data to confirm or refute this assumption.

The most important features of the geological structure in the frontal Kirthar and Sulaiman Ranges are as follows:

(1) There is a broad zone of steep foreland dip (and occasional overturning) which bounds and involves molasse sediments of the Sibi Trough at the mountain front (Figs. 2, 4 and 5).

(2) Jurassic (Chiltan Formation) limestones are elevated almost 9 km above the regional level on the internal side of the steep zone, yet no major displacement thrusts outcrop (Figs. 4 and 5).

(3) Only minor displacement thrust structures occur within the molasse sediments of the Sibi Trough on the external side of the steep zone. These intra-molasse thrusts, reflected by the Dezgat and Bannh anticlines at the surface (Figs. 2 and 4), are interpreted as out-of-syncline thrusts developed during formation of the major steep zone.

The seismic data are of limited value in the interpretation of the frontal mountain structures because lines do not extend across the steep zone. The main conclusions to be drawn, are that the pre-molasse stratigraphic section is essentially undeformed and that the Kirthar (limestone) Formation can be extrapolated from outcrop in the steep zone (unfaulted), directly into a flat-lying stratigraphic section at a regional level below the molasse.

We interpret the steep zone as a major frontal culmination wall (see Butler 1982) in the roof sequence of a duplex developed in the thick limestone units beneath a roof thrust in the Ghazij (shale) Formation. Since the outcropping Jurassic limestones are elevated about 9 km above their regional level within the duplex and undeformed stratigraphic sections occur immediately on the

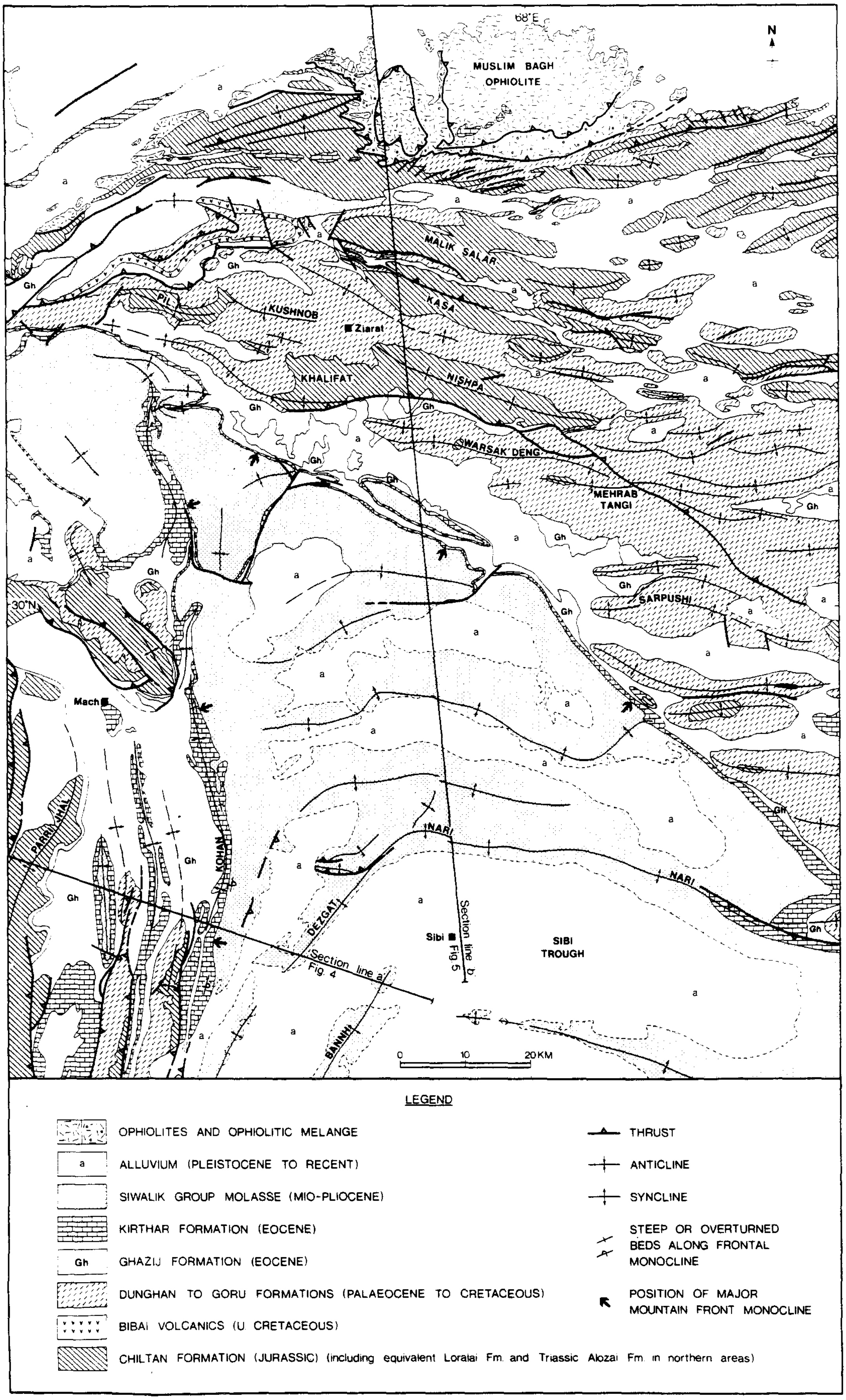

Fig. 2. Geological map of part of the Kirthar and Sulaiman thrust belts and the north-western part of the Sibi Trough. The location is shown as an inset on Fig. 1. The names on the map refer to the major surface anticlines, some of which appear on the cross-section in Fig. 5.

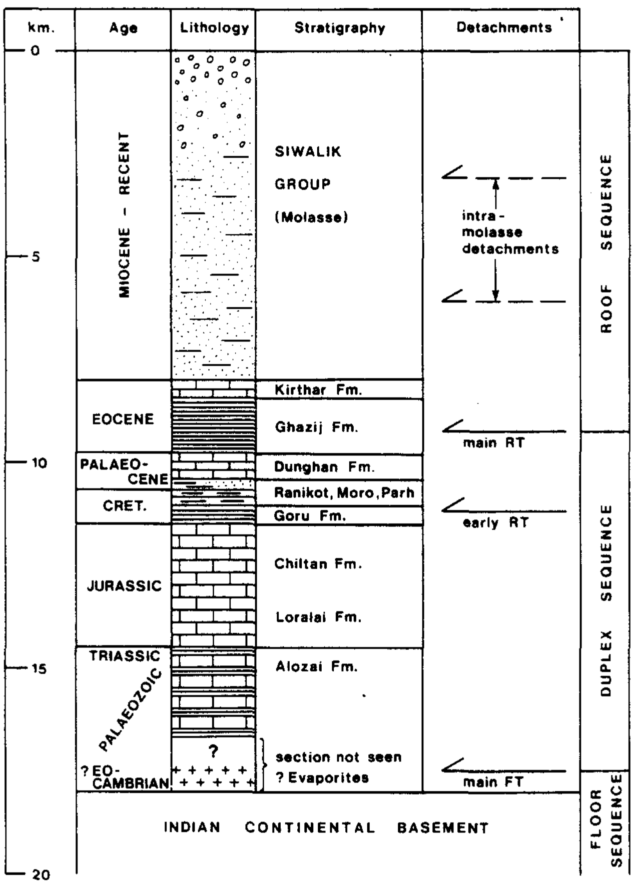

Fig. 3. Simplified stratigraphic column for the Kirthar and Sulaiman Ranges indicating the most likely detachment horizons.

foreland side of the steep culmination wall, then a blind thrust must exist immediately on the foreland side of the most external hangingwall cutoff within the duplex. Similar mechanisms of blind thrusting on the external side of the Northern Canadian Rocky Mountain foothills have been described by Thompson (1981). This means that shortening within the duplex could not have been accompanied by foreland-directed transport of the roof sequence. Instead, the roof sequence must have a backthrust sense of displacement relative to the foreland propagating imbrication of the limestones in the duplex (Fig. 6). This type of structure we refer to as a *passive-roof thrust*, which is equivalent to the "upper detachment" described by Jones (1982) in the Alberta syncline.

The Geological Survey of Pakistan have recognized a long backthrust structure in the vicinity of the mountain front along part of the length of the Kirthar thrust belt (Fig. 1) (Kazmi & Rana 1982). Our own studies in the Bolan Pass area and Sulaiman Range suggest that a passive backthrust exists along most of the length of the mountain front, forming the roof thrust of a *passive-roof duplex*. In a conventional duplex model the roof sequence would be displaced toward the foreland and we would expect to see some major structure caused by the accommodation of that displacement above the roof thrust. Instead, the only structures are relatively minor displacement out-of-syncline thrusts in the molasse above undeformed regional stratigraphy. The present day frontal culmination wall in the Kirthar and Sulaiman thrust belts projects up into the air and has been eroded to supply molasse sediment to the Sibi Trough.

It is likely that this thrust process also occurred at intervals during the development and propagation of the mountain front. As a result of such erosion, the preserved bed length in the roof sequence is considerably less than the restored bed length of rocks within the duplex. In the Bolan Pass area and in the Sulaiman Ranges, the roof sequence is preserved mainly in synclines which lie between the ramp anticlines of horses within the duplex (Figs. 2 and 4). One or both limbs of these synclines are usually steeply dipping (Fig. 4) and these steep zones may represent the successive positions

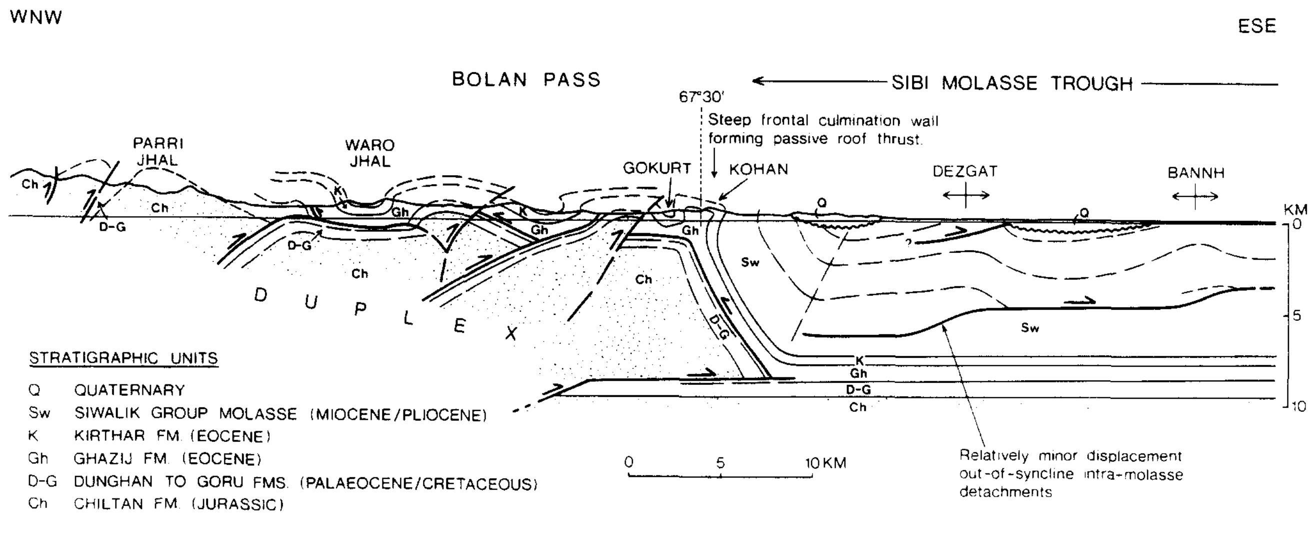

Fig. 4. WNW–ESE geological cross-section across the Kirthar thrust belt in the vicinity of the Bolan Pass. The line of cross-section is labelled "a" on Figs. 1 and 2. The cross-section is constructed from field data along with air photo and Landsat image interpretation. Seismic data over the Sibi Trough does not extend westwards as far as the steep zone, but demonstrates flat lying undeformed stratigraphy below the molasse, with relatively minor displacement on out-of-syncline intra-molasse detachments. Imbrication and shortening within the duplex causes about 9 km of uplift of the Jurassic Chiltan Formation above its regional level. Since no equivalent amount of shortening has been transferred into the foreland (undeformed sub-molasse stratigraphy and small intra molasse displacements only) then a blind thrust must be present at depth within the Ghazij décollement and a passive roof thrust must pass over the Jurassic Limestone imbricates.

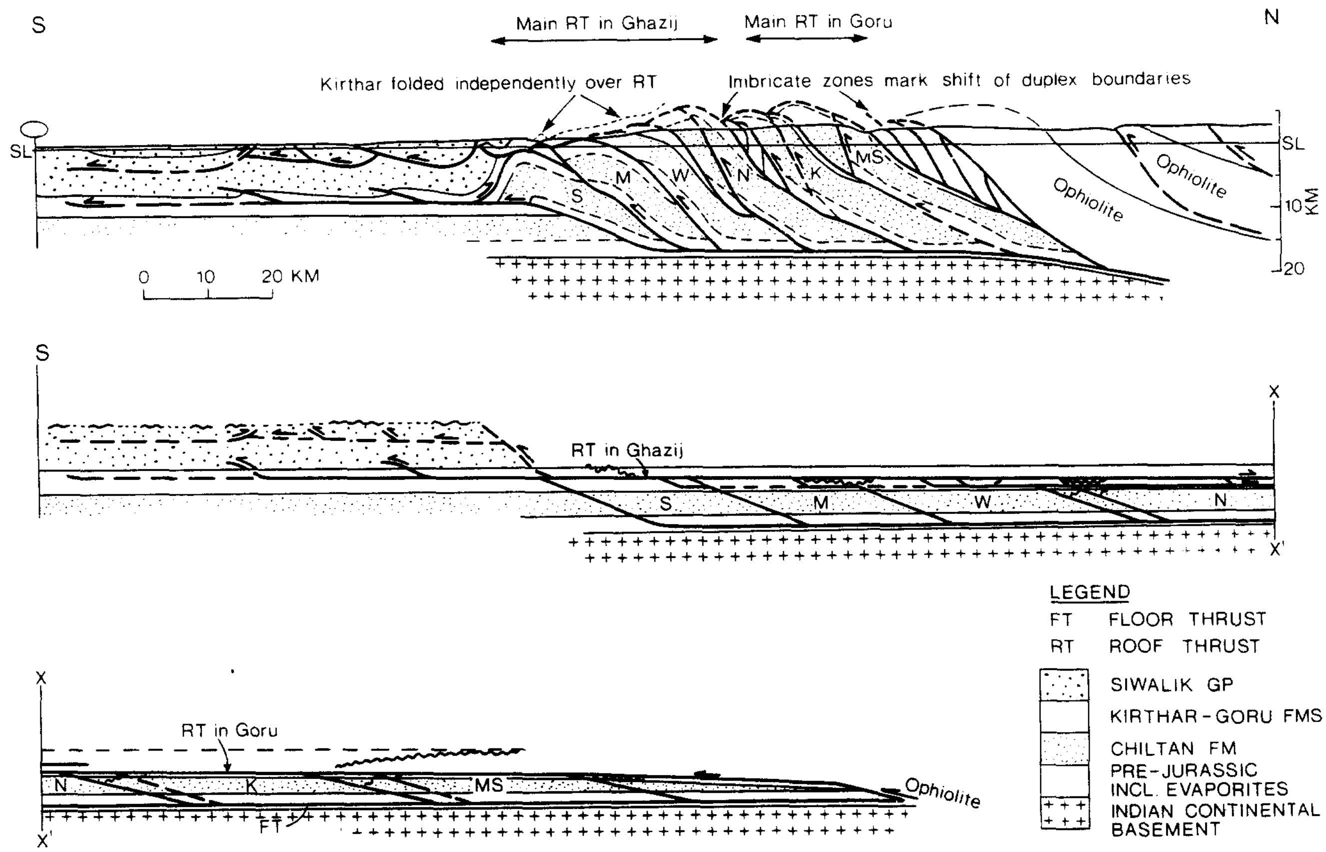

Fig. 5. Actual and restored N–S geological cross-sections across the Sulaiman Range. The line of cross-section is labelled "b" on Figs. 1 and 2. The same comments apply as those outlined in Fig. 4 caption. Letters identifying the major duplex horses are from individual mountains (shown on Fig. 2) formed from the ramp anticlines. From south to north these are: S, Sarpushi; M, Mehrab Tangi; W, Warsak Deng; N, Nishpa; K, Kasa; MS, Malik Salar.

during thrust propagation at which the passive roof sequence became emergent.

In the Sulaiman Range cross-section (Fig. 5), conventional duplexes on a relatively minor scale occur where the levels of the roof or floor thrust change. The transition from Lower Cretaceous (Goru) to Eocene (Ghazij) roof levels is marked by a minor Goru to Ghazij duplex which is overridden by the Jurassic slice to the north, i.e. it is a conventional duplex.

DISCUSSION: POSSIBLE STRUCTURES IN THE ROOF SEQUENCES OF PASSIVE-ROOF DUPLEXES

During development of a duplex, excess bed length rapidly accumulates in the roof sequence relative to the highly shortened duplex. This excess bed length may be eroded close to the mountain front, as in the Sulaiman Range, but if the roof sequence is not eroded, it is likely to become shortened by deformation occurring within it, not necessarily related to the structure of the underlying duplex. In the Bolan Pass the excess bed length in the roof sequence is taken up by hinterland-facing isoclinal folds. Another mechanism, not identified in this area in the field, but possibly present, is the development of passive backthrusts in the roof sequence. For a duplex forming purely by the passive-roof mode we may expect an overstep sequence (Butler 1982) of foreland-dipping passive backthrusts to develop in the roof sequence (Fig. 7). Such passive backthrusts have been recognized in the Alberta foothills of the Rocky Mountains (see Fig. 8b).

If passive roof duplexes are mainly restricted to moun-

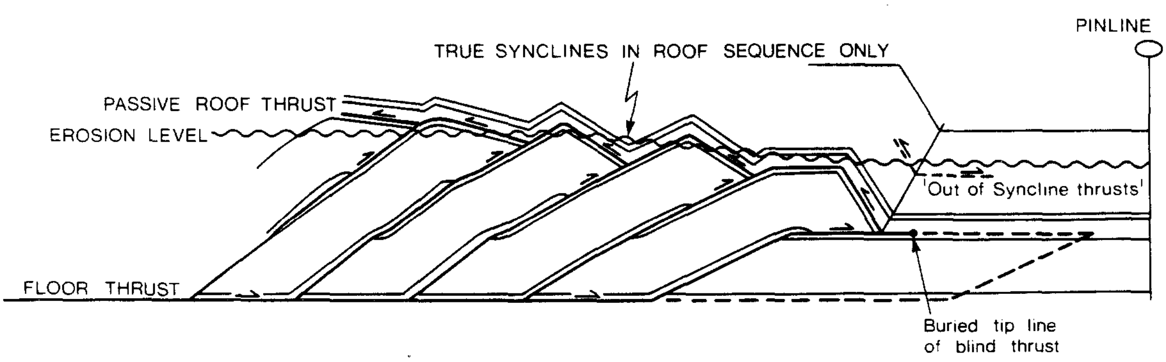

Fig. 6. Passive-roof duplex model: the roof sequence has backthrust sense relative to the forelandward propagated duplex.

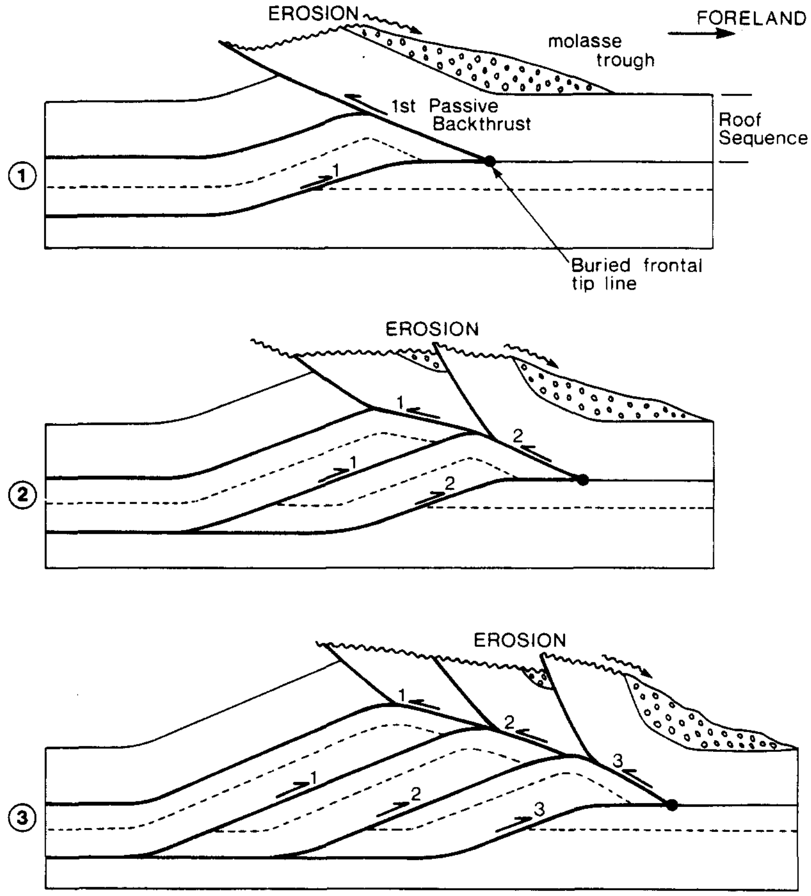

Fig. 7. Development of an overstep sequence of foreland dipping passive backthrusts in the duplex roof. 1–3 represent successive stages in the development of the duplex. Thrusts are numbered in order of development.

tain fronts it is not surprising that the geometry of their roof sequences is poorly documented. The structures there are becoming uplifted and emergent and a duplex roof is unlikely to be preserved for long. The key feature identifying the structure is the monoclinal forelandward dip at the mountain front with little major thrusting at outcrop.

Similar structures in other mountain belts

The concept of a backthrust overlying a frontal mountain duplex is not new. The term "triangle zone" was introduced by Gordy *et al.* (1977) to describe the region of opposed dip thrusts which extends along a great length of the Alberta foothills of the Rocky Mountains. Figure 8a is of a deformed and partially restored section across the Alberta syncline (after Price 1981), which demonstrates the passive-roof duplex geometry. The main features are the frontal mountain monocline (the Alberta syncline), the passive-roof thrust (the Waldron fault) and the foreland-thrusted passive-roof duplex which completes the "triangle zone".

Figure 8b is a modification of an original cross-section by Ziegler (1969) produced by Jones (1982) for the Athabasca Valley foothills. An important feature of that cross-section is the existence of foreland-dipping passive backthrusts within the roof sequence; a set of structures which we suggest in Fig. 7 but for which we have seen little evidence in the field in Pakistan.

As explained earlier, in the case of the Kirthar and Sulaiman examples, seismic data are of limited value in demonstrating the overall structure of the passive-roof duplex. Some impressive seismic data however, are presented by Jones (1982) for the Alberta syncline structure and demonstrate the buried frontal tip and passive-roof thrust ("upper detachment" of Jones) above the duplex. Further examples of passive-roof duplexes are discussed by Jones (1982).

A passive-roof duplex exists in the western frontal ranges of the Taiwan thrust belt, as illustrated by Suppe & Namson (1979), Suppe (1980a,b, 1981), Davis *et al.* (1983) and Suppe (1983). Suppe (1980a) demonstrated that no deformation extended west of the Taiwan mountain front and that the upper detachment of the duplex must be a passive backthrust. Microseismic data from the Taiwan thrust belt (Wu *et al.* 1979, Suppe 1981) has shown that the upper part of the stratigraphic section rides passively over a presently imbricating duplex wedge (Fig. 9). Numerous microearthquakes have occurred within the duplex, whilst the rocks of the roof sequence, and those beneath the sole thrust remain relatively aseismic.

Continuity of a passive-roof sequence

A problem of passive-roof duplex development is the

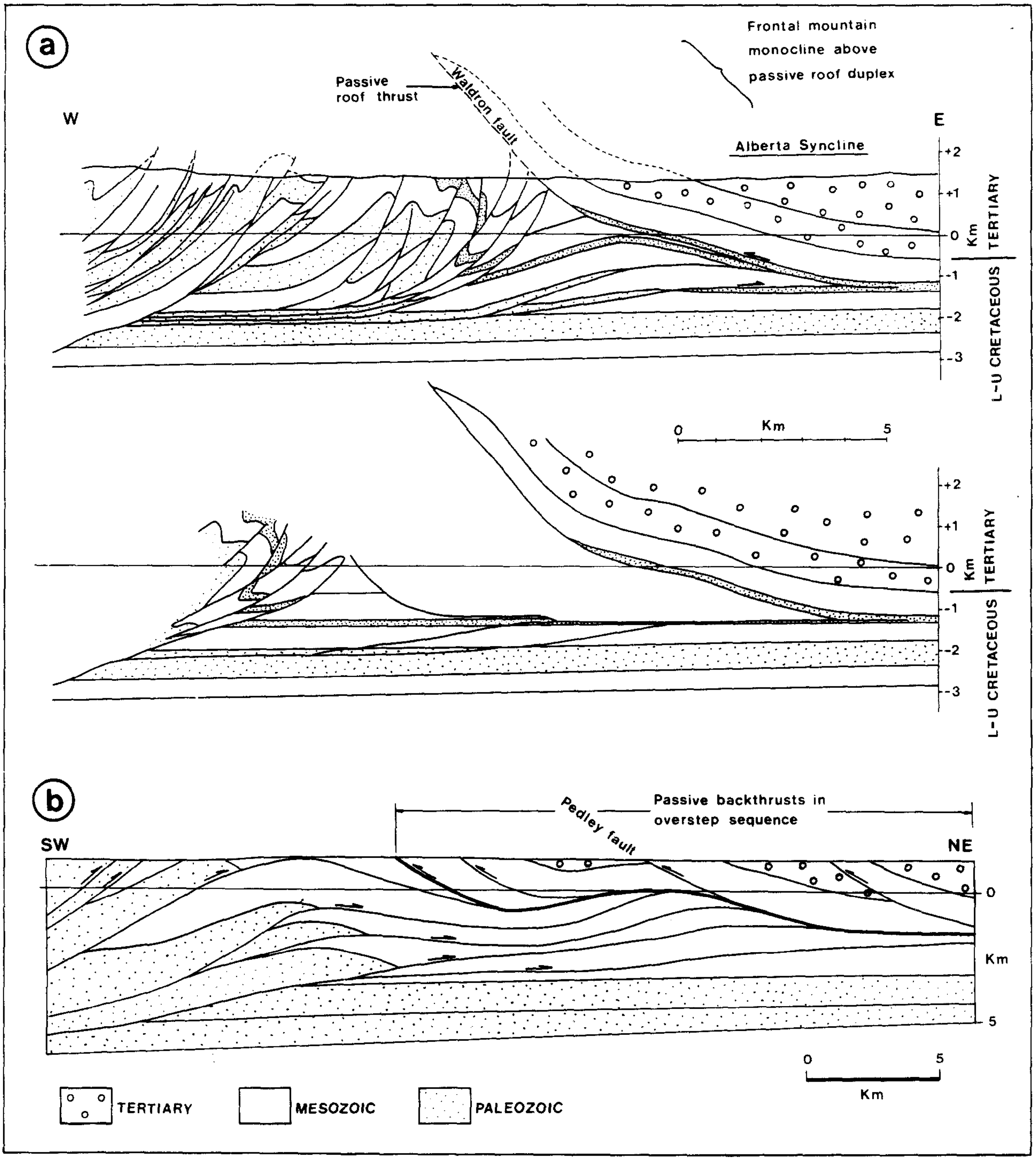

Fig. 8. Cross-sections across the eastern Rocky Mountain Foothills. (a) Deformed and partially restored E–W geological cross-sections across the Alberta Syncline at latitude 49°45'N (modified after Price 1981). (b) NE–SW cross-section across the Athabasca Valley Foothills showing backthrust imbricate stack in duplex roof sequence (modified by Jones 1982 after Ziegler 1969).

distance over which the upper backthrust (or roof sequence) can extend. In examples where the roof sequence is preserved, for example in the Athabasca Valley, Alberta (Fig. 8 cross-section *b*), it is dissected by several foreland-dipping backthrusts, each with a present length of up to 7.5 km (e.g. the Pedley Fault). It is conceivable that only this length of passive backthrust acted at any one time during duplex development, as indicated by Fig. 7. In contrast, in the Taiwan example, the length of continuous passive-roof sequence is considerably greater, up to 14 km (Fig. 9). Restoration of the western limb of the Alberta Syncline by Price (1981, see Fig. 8) indicates a single passive-roof backthrust extending some 13 km over hinterland-dipping horses. Jones (1982) predicts that 50 km of passive-roof sequence may have extended across the Alberta foothills. With such a limited number of well-documented examples it is difficult to estimate the dimensions of a passive-roof sequence in sections parallel to the dominant thrust movement direction. However, our feeling (based mainly on the analysis of the Pakistan structures and previously cited examples) is that the passive-roof mode of duplex deformation is most common in the vicinity of the mountain front.

Rather than inferring a single continuous passive-roof

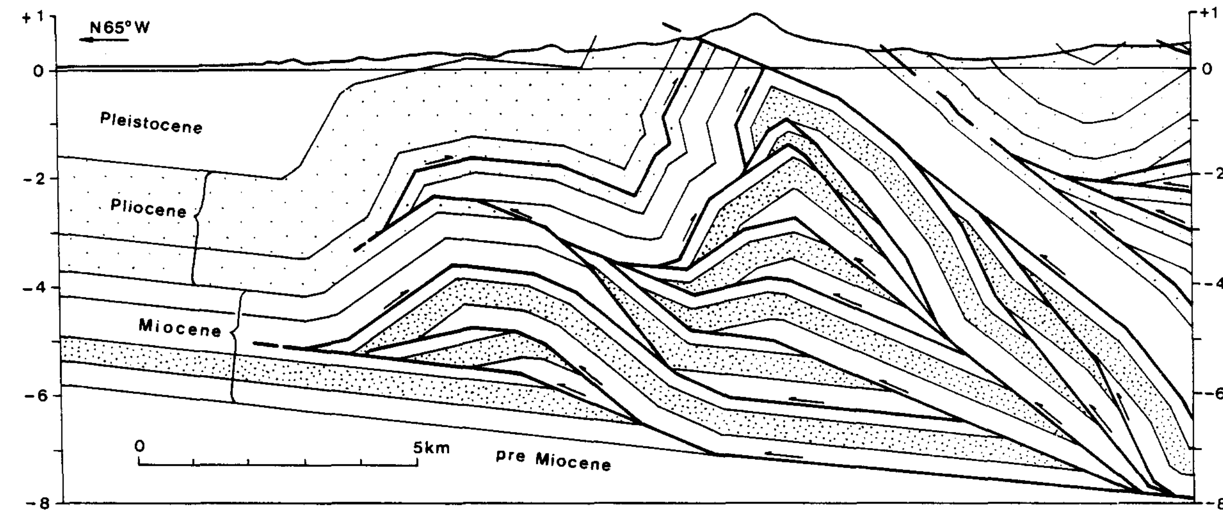

Fig. 9. Cross-section across part of the southern Taiwan thrust belt showing passive-roof duplex at the mountain front (modified after Suppe 1980a).

sequence which extends back over a large number of duplex horses, it is likely that the roof sequence becomes imbricated (as in Fig. 7) such that 'older' (more internal) segments of the passive-roof sequence become 'inactive' earlier, and are transported with earlier formed duplex horses toward the foreland. However, examples described by others, in particular the Brooks Range of Alaska (I. R. Vann pers. comm. 1983) suggest that continuous passive-roof sequences may extend several hundreds of kilometres across regional strike.

The common occurrence of backthrust structures hindward of mountain fronts and within the internal zones of mountain chains may reflect the further importance of passive backthrusting across entire orogenic belts.

CONCLUSIONS

(1) The passive-roof duplex is a duplex whose roof sequence has backthrust sense and remains relatively stationary during piggy-back style thrust propagation within the underlying duplex.

(2) Passive-roof duplexes can be inferred as a mechanism of orogenic contraction where the mountain front is marked by a forelandward-dipping monocline rather than a thrust, and only blind thrusts exist on the foreland side of the last mountain belt imbricate slice.

(3) To conserve bed length equality in and above a passive-roof duplex, there may be erosion of emergent imbricate slices of roof sequence. The passive-roof mode may therefore be of major importance near surface in the vicinity of the mountain front. However some examples appear to have a passive-roof sequence which extends for large distances towards the hinterland. The common existence of backthrusts in the internal zones of mountain belts possibly indicates a more general importance of the passive-roof mode of deformation.

(4) The emergence of passive-roof sequences in foredeep molasse basins (e.g. the Sibi Trough in Pakistan) may rework molasse sediments several times and produce multiple unconformities. This feature is not however restricted to emergent backthrusts, but occurs widely in areas where frontal imbricate fans emerge at surface.

(5) Overstep backthrust roof sequences with foreland dip may be a characteristic feature of passive-roof duplexes.

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