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Notes

The past of a future syntaxis across the Zagros

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Abstract: Longitudinal components of the Zagros mountain chain change in character and width across N–S trending zones of strike-slip transfer faults lying between 51° and 54° E. To the northwest, a fold-thrust belt with consistent SW vergence has a width of *c.* 220 km in front of an imbricate belt *c.* 160 km wide. To the southeast, an imbricate zone *c.* 80 km wide is fronted by a gently tapering festoon of upright periclines that is *c.* 350 km wide and punctured by over a hundred emergent salt diapirs.

Pre-Zagros stages of the transfer zones in the Zagros are preserved on the Arabian platform and the two most obvious bound what we call the incipient Qatar syntaxis. This is at an early stage of one of the many syntaxes that compartmentalize the Alpine–Himalayan mountain chain. We use structures in the Hormuz salt to map and gauge the tectonic pulse of basement blocks that jostled as ocean basins opened and closed diachronously like zip fasteners along the Tethyan margin of Gondwana. This incipient syntaxis was a lithospheric key that went up while others went down during the rifting and riffling, but not drifting, of the still-born Hormuz basin we call Proto-Tethys.

Like many older orogens, the length of the Alpine–Himalayan orogen is punctuated by syntaxes (Sarwar & De Jong 1979). These bends and tucks, *c.* 350–400 km apart, divide the orogen into compartments with different characters and histories (Fig. 1).

Recent studies of orogenic segmentation in Pakistan (e.g. Davis & Lillie 1994) have focussed on the mechanical differences between the thin-skinned contractional wedges between the syntaxes. Understanding how orogenic wedges differ in active orogens obviously has useful lessons for

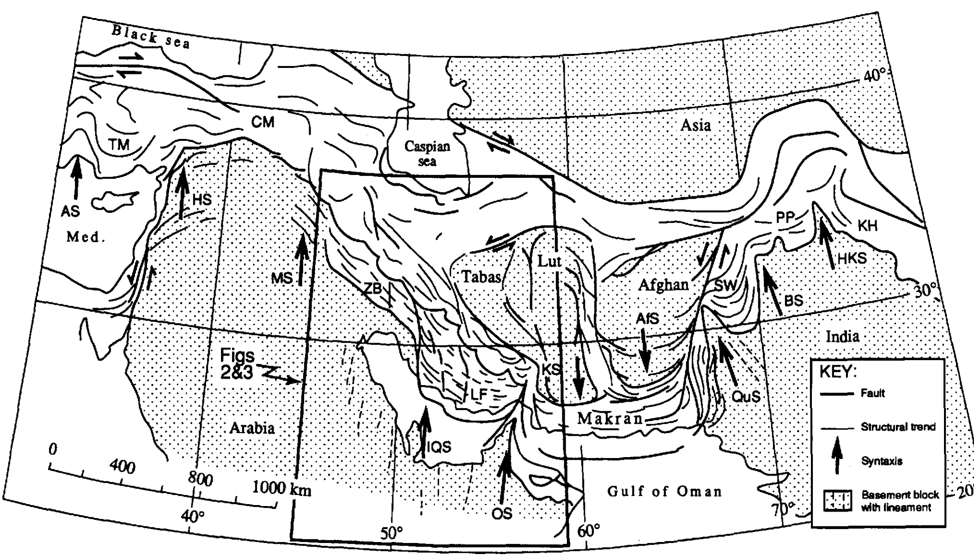

Fig. 1. Outline map of Alpine–Himalayan mountain chain indicating syntaxes and wedges and outlining the area considered here (after Sarwar & De Jong 1979; Alavi 1991; Dykstra & Birnie 1979). Syntaxes alternate with orogenic compartments from west to east: AS, Antalyo syntaxis; TM, Taurus mountains; HS, Halab syntaxis; CM, Caucausus mountains; MS, Mosul syntaxis; ZB, Zagros fold-thrust belt; IQS, Incipient Qatar syntaxis; LF, Zagros fold-diapir festoon in Laristan; OS, Oman syntaxis, KS, Kerman syntaxis, Makran wedge; AfS, Afghan Syntaxis; QuS, Quetta syntaxis; SW, Sulaiman wedge; BS, Bannu syntaxis; PP, Potwar plateau; HKS, Hazara-Kashmir syntaxis; KH, Kashmir Himalaya.

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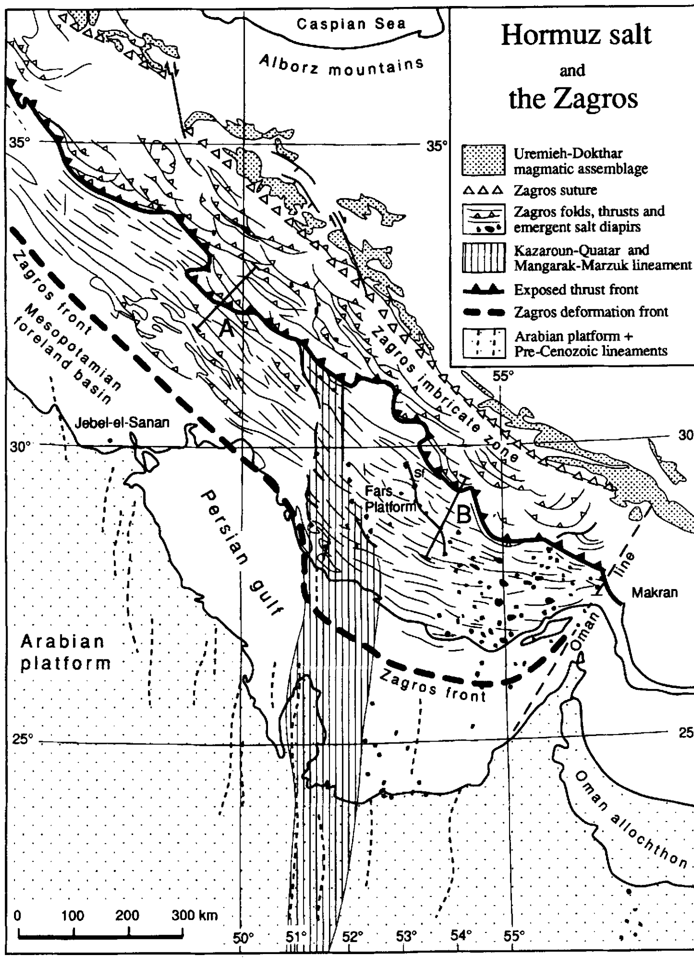

Fig. 2. The N–S Kazerun–Qatar and Mangarak–Marzuk lineaments extend 450 km across the Zagros between 51° and 53°E and extend 800 km further south onto the Arabian platform. Together they bound the incipient Qatar syntaxis. Notice that the topographic Zagros deformation front in the NW Zagros fold-thrust belt is behind the front defined using the shapes of oil fields on Fig. 3.

older orogens. The four segments discussed by Davis & Lillie (1994) represent different stages in the closure of an ocean basin and the subsequent contraction of sutured continental crust. The Neo-Tethyan ocean is still open to the south of the Makran wedge but has closed in both Pakistan to the east and in Iran to the west (Fig. 1). In the Makran, flysch-type sediments are accreting in a 300 km wide prism with a moderate 4° taper (Davis & Lillie 1994). To the east, beyond the Quetta syntaxis (Fig. 1), a thick continental margin sequence in the festoon-shaped Sulaiman wedge is at the stage where ocean–continent transitional crust is underthrusting Asia. Davis & Lillie (1994) speculated that the moderate 3° taper seen in profiles of the Sulaiman fold-thrust lobe might be due to ductile creep of warm carbonates as deep as 20 km. This novel scenario contrasts with the classic picture to the east, where a thin cover sequence detaches over a thin layer of salt. In northern Pakistan (Fig. 1), continental collision has doubled the thickness of the continental crust in two very different wedges on either side of the main Himalayan (Hazara–Kashmir) syntaxis. The Kashmir Himalaya is the most mature collisional wedge. It is a narrow (60 km wide) and strongly deformed fold-thrust belt with larger (7°) taper and constant SW vergence. This geometry is consistent with high traction along the base of the orogenic cover (Davis & Lillie 1994). By contrast, the Potwar Plateau to the west has an extremely gentle taper (≤1°) with remarkably little internal deformation in a thin

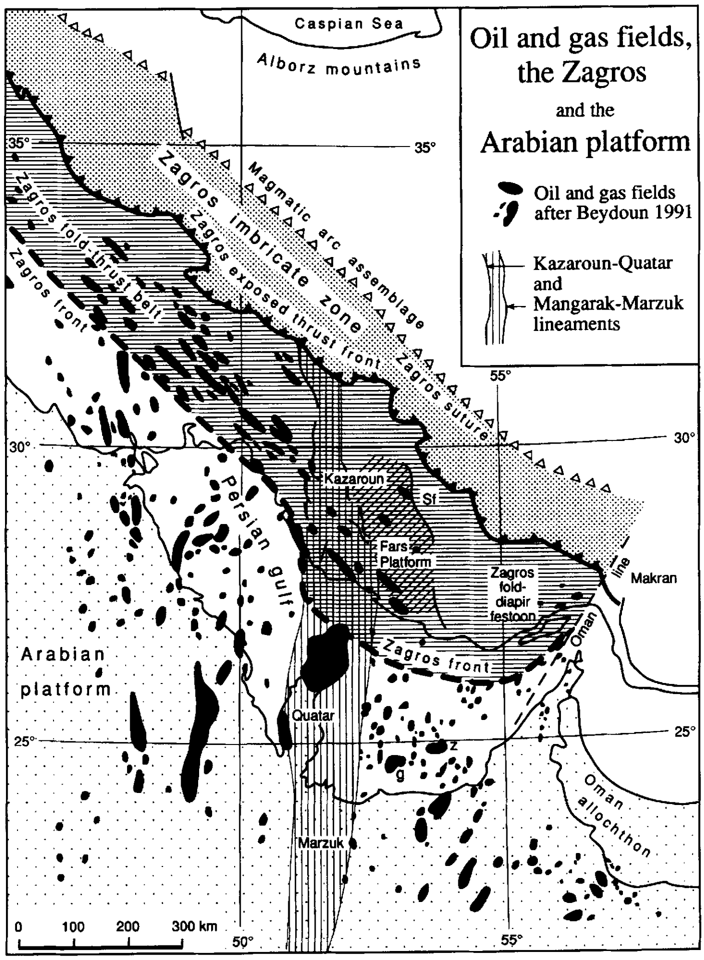

Fig. 3. The incipient Qatar syntax and the Zagros deformation front stand out on a map of the oil fields of the Middle East (adapted from Beydoun 1991). Sf is the Sarvestan fault. The Ghasha and Zakum fields are labelled g and z, respectively.

cover sequence taken to have transmitted compressive stresses over a salt decollement to the salt range along its leading edge (Butler *et al.* 1987).

This paper focusses on the tectonic development of the Zagros mountains west of the Makran. We distinguish two new wedges: the Zagros fold-thrust belt to the northwest of what we will refer to as the incipient Qatar syntaxis, and the Zagros fold-diapir festoon to the southeast (Fig. 2). These two wedges are additional to those listed by Davis & Engelder (1987) and Davis & Lillie (1994) and have exhibited different styles of deformation. We attribute these differences in style to the presence of Hormuz salt which accumulated unconformably on the Precambrian basement under one wedge but not under the other. We concentrate more on the history of the incipient Qatar syntaxis than the mechanical differences in the adjoining orogenic compartments. However, just as salt adds taste to a good meal, so salt can amplify the regional tectonics (Talbot 1992). We use the structures of Hormuz salt to feel the pulse of the northern margin of Gondwana as it was segmented by Tethyan basins; we then go forward in time and use Hormuz lithofacies to reconstruct the Neoproterozoic to mid-Cambrian tectonostratigraphy. Stamfli *et al.* (1991) considered the simple separation of Tethyan margins into Palaeo-and Neo-Tethys as inadequate and so inserted the gulf of Permo-Tethys into the story. Here we add earlier chapters (and details to Husseini (1989)) by distinguishing the lithofacies of an aborted palaeo-ocean that we call Proto-Tethys.

The Zagros Orogen

Previous subdivisions of the Zagros mountains (e.g. Stöcklin 1968) have been into four orogen-parallel zones (reviewed in Alavi (1994)): the Uremieh–Dokthar magmatic arc assemblage, the Sanandaj–Sirjan imbricate zone, the Simply Folded Belt, and the Mesopotamian foreland basin with the Persian Gulf (Figs 2 and 3).

The paleo-ocean of Neo-Tethys opened to the NE of the Sanandaj-Sirjan imbricate zone in the Permian (in Turkey) and Trias (in Iran). In the Late Cretaceous; Neo-Tethys closed along the Zagros suture lying between the magmatic arc and the imbricate zone. The complex Sanandaj-Sirjan imbricate zone (with some low-grade metamorphism) used to be separated from the unmetamorphosed Simply Folded Belt by the Main Zagros Thrust (Stöcklin 1968). However, this structure has recently been demoted from a single steep reverse fault or crush zone to a series of low-angle thrusts indistinguishable from others throughout the imbricate zone (Alavi 1994). The boundary to the imbricate zone shown on Figs 2 and 3 is merely the southwesternmost Zagros thrust that is exposed locally.

We here divide what has previously been known as the Simply Folded Belt of the Zagros into two new but distinct along-strike segments. These segments lie NW and SE of a zone that strikes N–S across the NW–SE tectonic grain of the Zagros between 51° and 53° E (Figs 2 and 3). This zone lies between what we call the Kazerun–Qatar lineament (to the west) and the Mangarak–Marzuk lineament (to the east). We interpret the intervening block as a future syntaxis that preserves the earlier stages of processes now obscured by continental contraction in Pakistan. This incipient syntaxis consists of the 460 km long N–S zone bounded by the Kazerun and Mangarak fault zones across the Zagros mountains, together with the Qatar and Marzuk lineaments that extend for a further 800 km southward across the Arabian platform (Figs 2 and 3).

The deformation front of the Zagros Simply Folded Belt has been driving the foreland basin in front of it as it has propagated episodically to the SW since the Late Cretaceous. The cover sequence is still undeformed on the Arabian platform but has been approximately doubled in thickness in the high plateau of the Zagros as a result of NE–SW shortening across the Simply Folded Belt. Hydrocarbon fields that are elongate along N–S or NNE–SSW trends on the Arabian platform are deformed to NW–SE Zagros trends behind the Zagros front (Fig. 3). The Zagros deformation front defined by the shape of oil and gas fields (Fig. 3) is intermediate in depth between Zagros fronts defined by seismicity and surface topography. Northwest of the Kazerun fault zone, the seismic front follows the south-

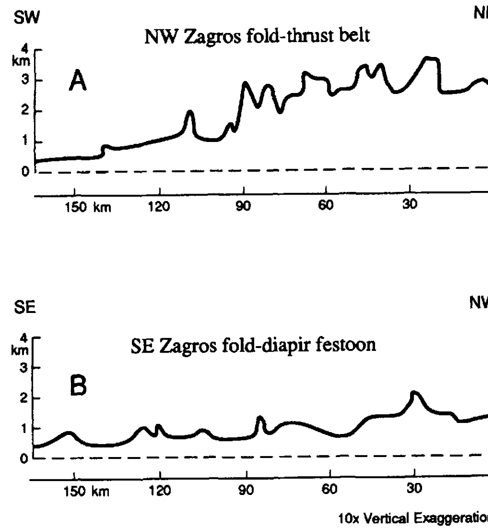

Fig. 4. Topographic profiles across the Zagros mountains along lines A and B indicated on Fig. 2.

western limit of earthquakes with kinematic solutions of NW–SE trending thrusts at depths of ≤15 to 20 km (Jackson & McKenzie 1988, Ekström & England 1989). This seismic front is offset approximately 160 km along the Kazerun fault zone. Six moderate-sized earthquakes along the Kazerun fault zone with NS strike-slip solutions have been attributed to right-lateral transtension along old faults in the basement (Baker *et al.* 1993).

At the surface, the topographic front of the Zagros mountains is currently about 50 km behind the deep seismic front to the NW of the Kazerun fault zone, but more nearly coincident with the 50 fathom water-depth contour we take to bound the topographic front SE of the Mangarak fault zone. The topographic front of the Zagros is offset by *c.* 200 km along the incipient syntaxis.

Three transfer zones and the incipient Qatar syntaxis

Kent (1979) described three right-lateral transcurrent fault zones decorated by salt extrusions trending obliquely across the Zagros: the Kazerun, Mangarak and Sarverstan fault zones (Fig. 2). These zones display complex anomalous relationships between strike-slip faults that trend NS, NNW or NE, and Zagros folds and thrusts that trend NW–SE. All three are narrow zones of low topography bordered by broad blocks with higher topography. All terminate in strike-parallel thrusts with NW–SE Zagros trend (Figs 5 and 6). The northern

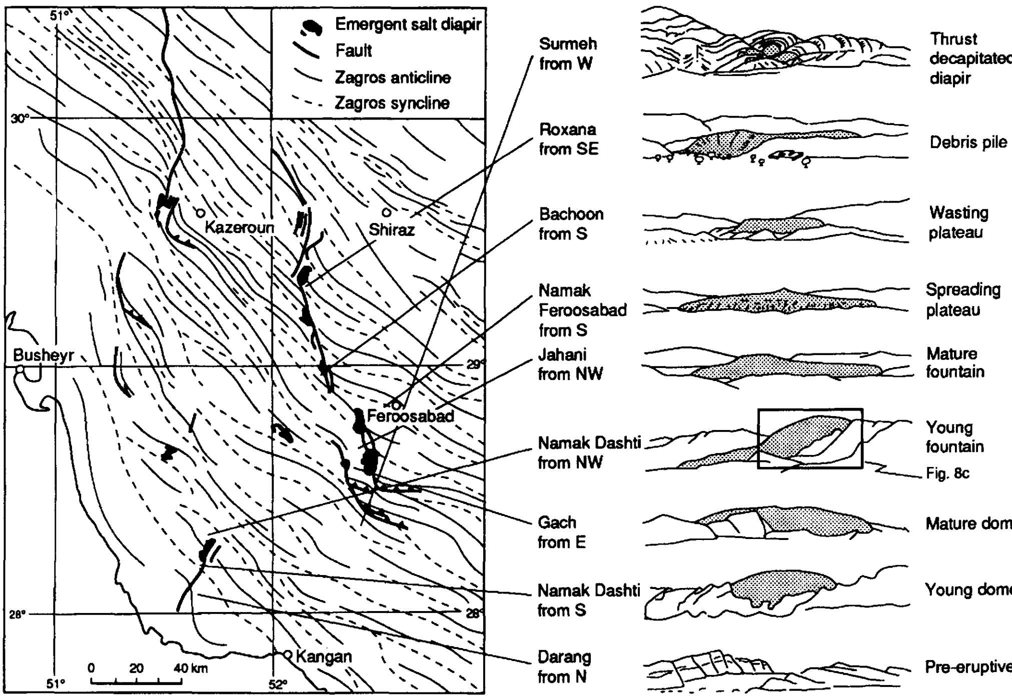

Fig. 5. Map of the Kazerun and Mangarak fault zones (to left and right, respectively) and sketches (traced from photographs) of some of the (stippled) Hormuz extrusions along them.

end of each fault zone swings to the NW; it is unclear whether this curvature is primary or is due to an increase in Zagros shortening towards the suture, or to left-lateral strike-slip shear along the suture.

The Kazerun fault zone is 450 km long, and the Mangarak fault zone is 150 km long some 60 km to the east (Fig. 5). About 100 km still further NE, the 100 km long Sarvestan fault zone trends NNW near Fasa in the inner Zagros (Kent 1979). We take the Sarvestan fault zone, the least well known transcurrent fault zone across the Zagros and one that we have not worked along, to bound the north-eastern corner of the Fars platform. The Fars platform is an area with a comparatively thin Permian to Eocene cover sequence, not pierced by salt structures, that lies between the Mangarak fault zone and 54°E (Fig. 2).

The Kazerun and Mangarak fault zones are a pair of anastomosing fault zones that trend generally N–S across the Zagros Simply Folded Belt between 51° and 53° E (Fig. 5). They act as oblique footwall ramps that transfer NE–SW shortening across the steep and narrow Zagros fold-thrust belt in the NW from the wider Zagros fold-diapir festoon with its lower taper in Laristan in the SE (Kent 1958). The fault blocks to the east of both the Kazerun and the Mangarak fault zones are structurally higher and more deeply eroded than blocks to the west (Kent 1979). This difference in structural level can reach 5 km in the north but varies with location and depth; at the south end of the Kazerun fault zone, the offset in the top of basement was thought to be *c.* 1–1.5 km (by Templeton, personal communication 1977) while Jurassic beds are offset only *c.* 100 m.

Both the Kazerun and Mangarak fault zones consist of en-echelon segments of steep right-lateral strike-slip faults with local throws that are both reverse and normal. However, whereas anticlines die out towards older faults along the Kazerun fault zone (Baker *et al.* 1993), anticlines culminate and are offset by younger faults along the Mangarak fault zone (Figs 5 and 6). With NNW trends oblique to the main NW Zagros trend, one might expect right-lateral strike-slip transfer zones to be generally transpressive. However, both zones are decorated by diapirs of Hormuz Formation that rose into rhombic cavities indicated by offsets of the traces of anticlines (Fig. 6). Such cavities play the role of (upside down) pull-apart basins at intervals of *c.* 22 ±6 km. Later, when discussing Zagros kinematics, we will argue that these salt bodies are reactive synshortening diapirs that have risen, or are still rising, wherever Zagros anticlines are offset along

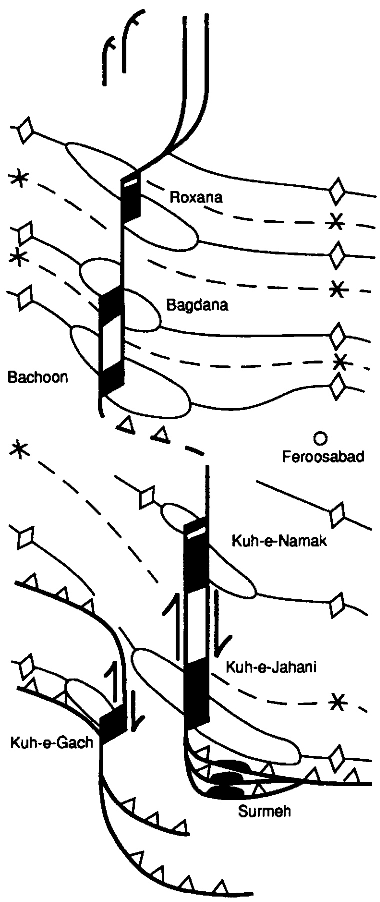

Fig. 6. Current kinematics of the Mangarak fault zone stylized to an almost continuous pattern of faults. Salt extrusions are in black; elliptical outlines are anticlinal culminations.

individual strike-slip faults (as diapirs have been interpreted to have risen along jogs in strike-slip faults in the Sverdrup basin in Arctic Canada (Schwerdtner & Osadez 1983)). Along the Mangarak fault zone, five diapirs have risen into rhombic openings pulled apart at releasing right-lateral en-echelon offsets along four or five parallel strike-slip faults (Fig. 6). Thrusts splay southeastward from the southern end of each segment of the Mangarak zone; one such group of thrusts dices a beheaded pre-Zagros diapir now devoid of salt at Surmeh (top right on Fig. 5)).

Changes in tectonic style both along and across the Kazerun and Mangarak fault zones are due to more than merely the level of erosion of thin-skinned fault zones (Kent 1979). This is because deformation styles relate to changes in thickness and facies at several levels in the regional stratigraphy between the Present and Precambrian. We will describe some of these changes later and show how the alignment of salt extrusions along the faults, together with their current seismicity (Baker *et al.* 1993), suggest that these zones are due to repeated reactivation of Precambrian faults in the underlying basement. The Kazerun and Mangarak fault zones represent fundamental along-strike divisions of the Zagros Simply Folded Belt into the compartments described in the next two sections.

NW Zagros fold-thrust belt

NW of the Kazerun fault zone, the Simply Folded Belt of the Zagros is a long (1400 km), straight and narrow (220 km) seismically active wedge with a profile taper of *c.* 2° (Fig. 4). The NW Zagros fold-thrust belt stretches *c.* 1400 km between the Kazerun fault zone and the Mosul syntaxis in front of a 160 km wide Zagros imbricate zone (Fig. 1). Thrust-cored anticlines are 30–50 km long, 8–16 km wide and 2–3 km in amplitude, and verge consistently to the SW in a 6–10 km thick cover sequence consisting largely of platform carbonates.

No diapirs of Hormuz salt reach the surface in the NW Zagros fold-thrust belt (Fig. 2) and we suppose that any underlying Hormuz sediments are anhydrite or carbonates with only subsidiary salt. As well as a lack of emergent diapirs, there are also comparatively few emergent thrusts in the NW Zagros fold-thrust belt (Fig. 2). We follow O'Brien (1957) and attribute the structural style (and the 2° taper) of the fold-thrust belt (Fig. 4) to control by a shallow Miocene salt rather than a deep Hormuz salt. The disharmony and different wavelengths of folds above and below the Miocene salt demonstrate décollement along it (Talbot *et al.* 1987). Letouzey *et al.* (in press) show how a shallow décollement results in blind rather than emergent thrusts. Their models explain how anticlines with fishtail mapforms and triangular zones in profiles are so common in the NW Zagros fold-thrust belt (O'Brien 1957).

SE Zagros fold-diapir festoon in Laristan

The long straight and closely-spaced thrust-cored anticlines of the Zagros fold-thrust belt abruptly broaden SE of the Mangarak and Sarvestan fault zones into an arcuate festoon of short wriggly and relatively gentle folds punctured by *c.* 120–130 emergent diapirs of Hormuz salt in Laristan. The SE Zagros fold-diapir festoon has a profile taper of <1° (Fig. 4) and reaches a width of *c.* 360 km between boundaries tucked 500-600 km apart. The tight eastern tuck in the festoon is along the NE-trending western boundary of the Oman syntaxis which separates the Zagros continent–continent collision zone from the Makran subduction zone offshore

(Figs 1–3). The SE Zagros fold-diapir festoon is characterised by upright and symmetric periclines with doubly plunging sinusoidal axes only a few tens of kilometres long and *c.* 15 ± 3 km apart on either side of tight synclines. Whereas diapirs are localized in fault zones along the incipient syntaxis, they are spatially dispersed in Laristan. The festoon was originally underlain by a thickness of Hormuz salt (estimated at 1–1.5 km (Kent 1970)) sufficient for it to rise diapirically through a cover sequence 6–12 km thick.

The Salt Range in Pakistan (Fig. 1) defines a broad arc around the gentle (<1°) taper of the Potwar Plateau that is also detached above a (Hormuz-equivalent) salt (Butler *et al.* 1987). In contrast to the many anticlines and intrusions in the SE Zagros fold-diapir festoon, the Potwar Plateau is almost unfolded and devoid of diapirs. We attribute this difference to the salt being significantly thicker beneath the SE Zagros fold-diapir festoon than beneath the Potwar Plateau.

The pre-orogenic histories of the Zagros and its future syntaxes could be laboriously reconstructed within the Zagros mountains themselves. However, we take a simpler approach and look southward, beyond the Persian Gulf in the foreland basin, to the Arabian platform. Here, in platform sediments still untouched by the Zagros orogeny, precursors of the structures in the syntaxis are represented by pre-orogenic diapirs rising from salt pillows (Kent 1987). All three transfer zones across the Zagros are in line with clear N–S lineaments on the Arabian platform (Figs 2, 3 & 9). We will refer to the two lineaments extrapolating the Kazerun and Mangarak fault zones *c.* 800 km southward as the Kazerun–Qatar and Mangarak–Marzuk lineaments because they bound local structures with those names.

Salt pillows

N–S or NNE–SSW lineaments in the Zagros foreland basin and on the Arabian platform are constrained by the locations and shapes of the many giant and few supergiant oil and gas fields (Fig. 3). Most of these fields occur in gentle and essentially unbroken periclines in Tertiary sediments with flank dips of <5° (Kent 1979, Alsharhan 1989). The periclines are thought to be draped over deep pillows of Hormuz salt that were triggered by early to mid-Cretaceous differential sedimentation onto overburden weakened by movements along old-established basement faults (Alsharhan 1989).

On the Arabian platform to the NW of the Kazaroun–Qatar lineament, these pillows and their drape folds are elongate with a roughly N–S orientation known as the Arabian trend (Edgell 1992). To the SE of the Mangarak–Marzuk lineament, some of the drape folds on the Arabian platform trend NNE (Fig. 3). Many of the emergent diapirs onshore in Laristan may also have been aligned in lines that rose from pillows elongate along a NE trend before their pattern was distorted by Zagros shortening (Kent 1979, Fig. 7).

A large N–S trending pillow indicated by thinning of Jurassic cover at the southern end of the Kazerun fault zone is both the northernmost and earliest pillow reported in the literature (Kent 1958, p. 259). Pillowing of salt generally began in Jurassic times in the west of the region (Beydoun 1991, p. 58) and in the Early Cretaceous in the east (Alsharhan 1989, p. 272). The same tendency to young eastward is seen in the oil and gas fields. Another structural pattern is that salt pillows on the platform tend to change northward to diapirs-rooted-to-pillows under the foreland basin, and then to diapirs-emergent-from-deflated-pillows in the Zagros orogen.

We will return to considering tectonic timing after explaining how the diapirs register the tectonic pulse (stresses) and sample the stratigraphy of the deep décollement that controls the regional tectonics and hydrocarbon accumulations. Here we interpret the salt structures on the Arabian plate as having been initiated by a wave of instability that travelled eastward along the northern edge of Gondwana long before the closure of Neo-Tethys led to the subsequent Zagros deformation. We take most pre-, syn- and post-Zagros salt structures to have been elongate or aligned in N–S or NNE trending rows along narrow fault zones separating large stable blocks that were jostled by a succession of tectonic movements which we shall discuss later. Two possible exceptions are the Ghasha and Zakum fields (g and z on Fig. 3), which trend W–E in the southern gulf and may record the first distant effects of Zagros shortening (Alsharhan 1989, p. 271). This shortening may have been transmitted through a stiff cover acting as a stress guide as described in the Potwar Plateau (Butler *et al.* 1987).

Diapirs of Hormuz sequence

There is a vast literature on the extrusions of Hormuz salt in the Zagros mountains and Oman (see references in Kent (1958, 1979, 1987), Gansser (1960), Stöcklin (1968) and Talbot & Jarvis (1984). These spectacular fountains and flows of Precambrian salt spreading over Recent sediments offer subaerial examples of submarine sheets of allochthonous salt currently spreading off the shores of the US Gulf coast (Talbot 1993) and Yemen (Heaton *et al.* in press). Gravity spreading of salt extrusions has been common in other sedimentary basins in the past (e.g. northern Germany in the Campanian, Nordkapp basin in the Jurassic).

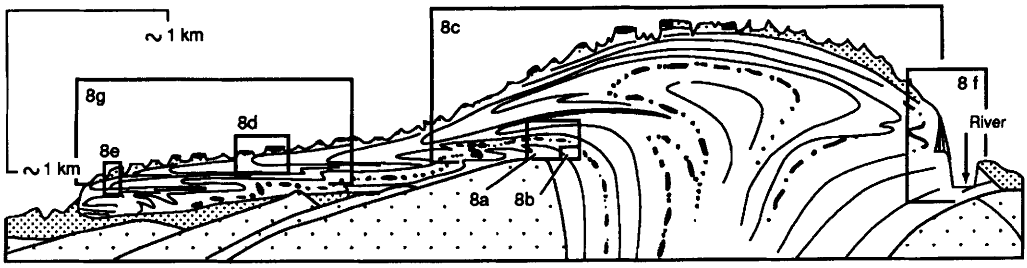

Fig. 7. Cartoon of internal structures based on salt fountains along the Kazerun and Mangarak fault zones. Boxes indicate locations of photographs in Fig. 8. Bedding is picked out by colour banding or boudinaged limstone beds and subparallels both non-slip and free salt boundaries. Steep layering in the orifice spreads in extrusive salt to parallel the parabolic top surface which is fretted to pinnacles by dissolution. The namakier (salt sheet) advances like a tank track, with recumbent flow folds indicating where it has surmounted obstructions.

In front of the high Zagros, diapirs are typically 5–10 km across and extrude up to 1.5 km above sea-level before spreading several kilometres beyond their vents as sheets of allochthonous salt known as 'namakiers', or glaciers of salt (from *namak*, the Farsi for salt). Each of the extrusions along the Mangarak fault zone shows a different stage of evolution (Fig. 5). Topographic domes of salt (Kuh-e-Gach, Fig. 5) later develop the distinctive parabolic profiles of viscous fountains with a summit dome (Kuh-e-Jahani and Namak, Dashti) that collapses (Talbot 1993) when the deep source is exhausted or disconnected (Kuh-e-Namak, Feroosabad). After that, the emergent salt is dissolved to leave a debris-filled crater (as at Roxana, Fig. 5).

Although bedding survives in extruded salt as compositional layering, all depositional salt fabrics have recrystallized. Layering in the salt (or in residual soils after salt dissolution) generally parallels the rigid bottom and side boundaries of all salt bodies, wherever they are exposed (Talbot 1979, 1993). This is so whether the country rock contacts are subvertical in exposed vents, have irregular dips away from the vent, or are subhorizontal over bedrock or recent alluvium ± debris shed from the advancing salt flow (Fig. 7). Traced upward, the axial surfaces of upright folds exposed in deeply eroded vents (Figs 8a, b) turn to either parallel gentle (<20°) slopes controlled by flow (Fig. 8d), or steeper slopes truncated by erosion (Fig. 8f).

Two thin namakiers spread from the salt fountain at Kuh-e-Namak (Dashti) and flow down the flanks of an anticlinal culmination disrupted by the southern end of the Kazerun fault zone (Talbot 1979). They are sufficiently steep not to be mantled by thick soils (Fig. 8c) and their internal deformation structures and fabrics are well exposed (Fig. 8d). Rather than erode their channels, namakiers flow over pre-existing topographies. Trains of internal flow folds and ductile shears thin and repeat the layers, and separate, mill and disperse inclusions wherever the flowing salt thickens to pass channel obstructions (Talbot 1979). A 'menacing maze of salt pinnacles . . . often protected by perched erratic blocks' (Kent 1970, p. 80) characterizes vigorous young extrusions. Older salt extrusions (Fig. 5) are progressively cloaked by insoluble debris in which conical collapsed craters eventually coalesce to form badland topographies (Fig. 8g).

The basic structure of each namakier is that of a recumbent sheath fold with a down-slope profile like a tank-track (Figs 6 and 8d). Isoclinal, similar-type recumbent folds (Fig. 8d and e) characterize the distal portions of salt sheets around all of the salt extrusions along the Mangarak fault zone (Fig. 7). The basal levels of extrusive salt are typically dirty mélanges smeared to conformity with the irregular tops of water-sorted deposits shed from the advancing salt front. Namakiers in the Zagros flow over their own debris like other nappes that have advanced over emergent thrusts. Whereas some namakiers have the steep snouts overriding terminal moraines typical of advancing ice flows (Fig. 8g), others have the distal feather edges characteristic of retreating glaciers.

Current salt flow

A matter of great debate during optimistic discussions in the 1970s about storing radioactive wastes in salt diapirs (Gera 1972) was whether the namakiers of Iran are still flowing (Kent 1970) or only flowed temporarily in the past like hot lavas (Gussow 1966).

The first field study devoted entirely to a Zagros salt extrusion established that Kuh-e-namak (Dashti) expands and contracts as an elastic solid

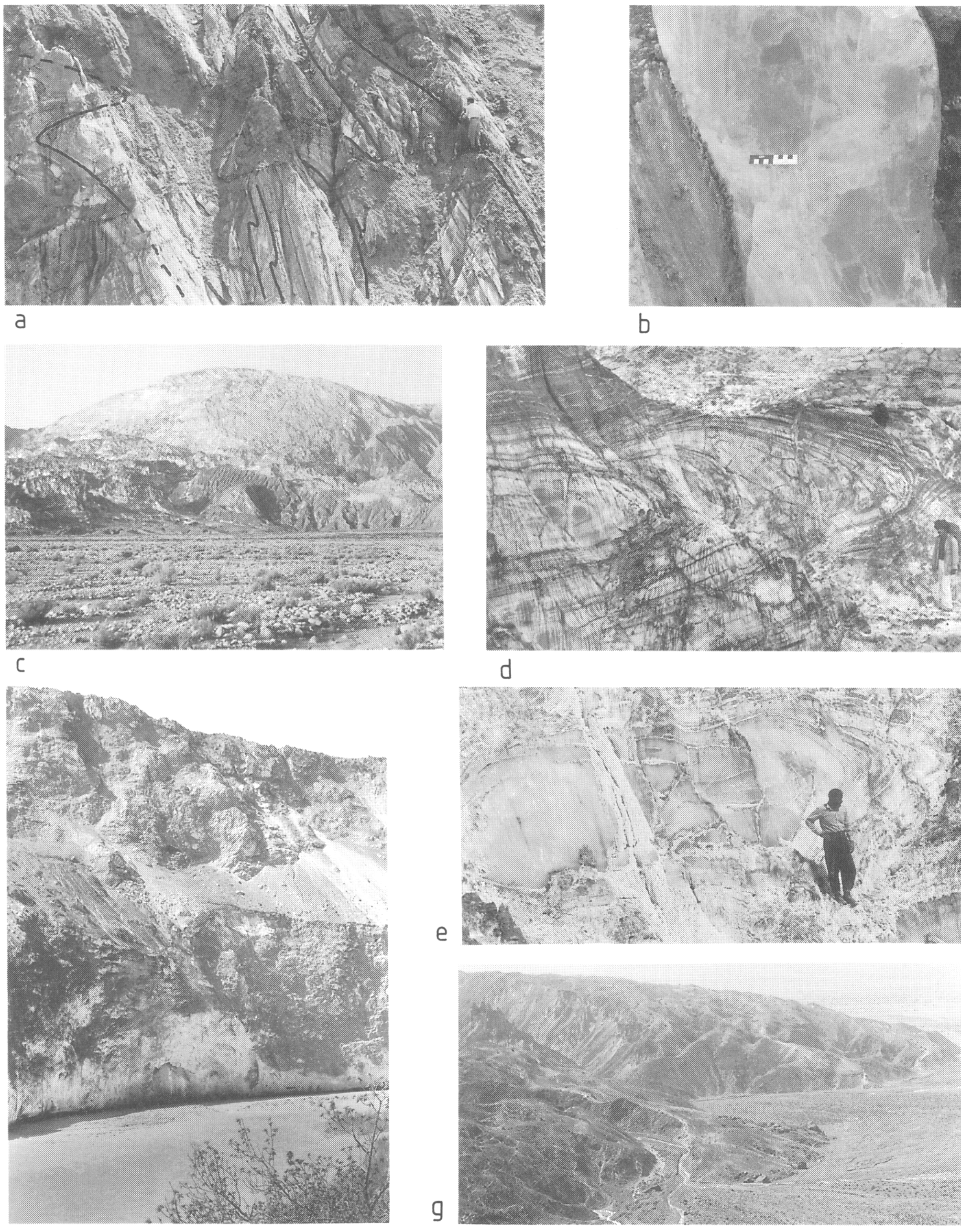

Fig. 8. Photographs of (**a**) steep layering (emphasized by black lines) in the vent exposed at Bachoon (see Figs 5 or 6 for locations); (**b**) steep pegmatite of halite to bottom right of area in photo (**a**). Scale bar is 10 cm long. (**c**) The salt fountain at Kuh-e-Namak (Dashti) seen from the NW. The northern namakier flows out of the picture to the left. (**d**) The tank-track recumbent fold just behind the snout in the northern namakier at Kuh-e-Namak (Dashti). (**e**) An individual pegmatite of halite repeated by recumbent folds in the SE snout of Kuh-e-Namak (Feroosabad). (**f**) River cliffs (*c.* 100 m high) of perhaps *c.* 80 vol% of salt partially obscured by accumulations of grey impurities along the northern edge of Kuh-e-Jahani. (**g**) Since the clean younger Hormuz salt in the southern snout of Kuh-e-Jahani dissolved, this lobe has consisted of grey remnant soils rich in anhydrite or gypsum.

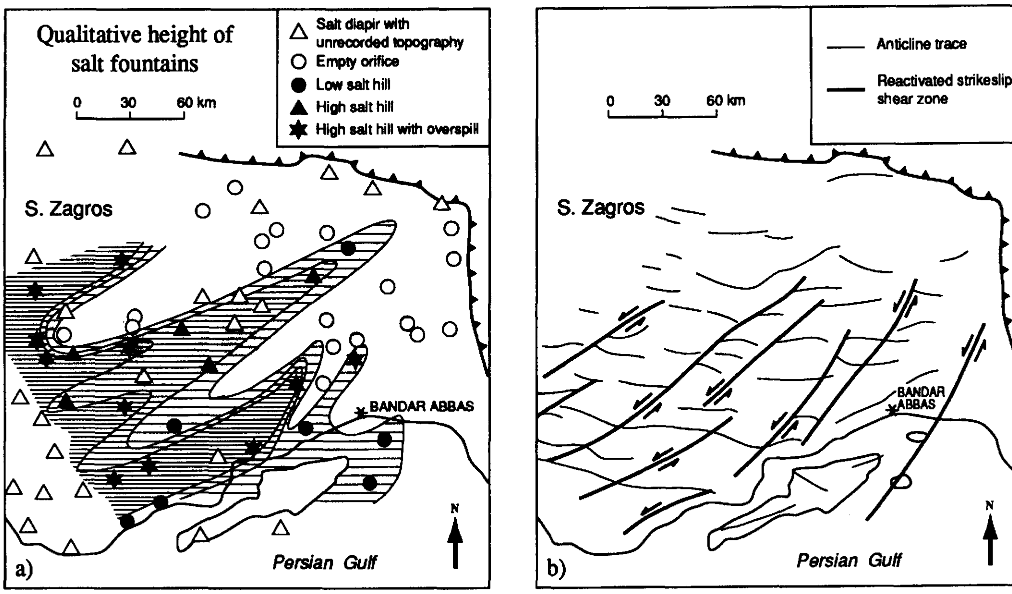

Fig. 9. Relative heights of salt extrusions (**a**) vary much more than the local rainfall, which is *c*. 100–200 mm a^{-1} near Bandar Abbas in Laristan. Contours of qualitative extrusion height (data mainly from Harrisson (1930) and Talbot (1992)) follow neither contours of rainfall nor the trends of Zagros folds (**b**); instead they follow a pattern of strike-slip faults oblique to the Zagros trend (Fürst 1979).

when it is dry, but flows as a ductile fluid after a fractured brittle lid, about 10 m thick, is dampened by rain (Talbot & Rogers 1980). Daily avalanches from a cliff high above the southern namakier during the rainy season signal ductile flow in the summit dome. It is not only direct rainfall that softens extrusive salt; brine springs flow from near the summit of many salt extrusions even in the dry season, and drilling into salt in the Iranian oil fields has produced large volumes of brine at very high pressures (Gansser 1992, p. 839).

Field studies inspired a series of laboratory experiments that explain how <0.1 wt% of enclosed brine can weaken confined rock salt to an essentially viscous but crystalline fluid (Urai *et al.* 1986). Dispersed cubic inclusions of brine can be smeared by very low shear stresses into continuous films that act as dramatically mobile boundaries to halite grains. The rock mass flows by ions dissolving from damaged grains of halite, diffusing across the brine-filled grain boundaries, and precipitating new undamaged grains of a different shape (Urai *et al.* 1986). This process becomes cryptic after stress-drop annealing (Urai *et al.* 1986), when surface tension disperses brine-films back through rounded brine fingers to isolated brine inclusions that start as spheres but mature to cubes. Whereas rocks have long been known to flow by thermally assisted creep, field studies of the surface flow of salt in the Zagros helped towards the recognition that other metamorphic rocks flow by water-assisted dynamic recrystallization.

Other theoretical problems raised by the extrusions of the Hormuz sequence in Iran and Oman were the space problem (Kent 1979), and how it was possible for the salt to lift large dense inclusions at least 5 km up to the surface (Gansser 1992). The space problem can be solved by the salt having risen reactively along the spaces opened along faults. Jackson & Vendeville (1994) considered the space to be created by normal faults, we consider the space to be created at releasing bends along strike-slip faults (Fig. 6). The inclusion problem was solved by numerical models (Weinberg 1993) showing that salt rising at documented velocities of a few millimetres per year, with experimentally derived power-law exponents of stress of $n = 4$ to 5, can indeed lift the largest salt-entrained blocks known in Iran (5000 m × 2000 m × 125 m).

Flow of rock salt at the surface emphasizes the effectiveness of salt décollements at the higher temperatures and pressures expected at depth.

Extrusion topographies gauge current tectonic pressure

Past workers considered the topographies of extrusions of the Hormuz sequence to vary more or less systematically across the Zagros (Ala 1974, Kent

1979). They reported vigorous salt fountains in the lower rainfall (100–400 mm a^{-1}) of the coastal ranges but thick piles of insoluble Hormuz debris burying dissolved salt in regions of higher precipitation (400–800 mm/a) inland. However, whether an extrusion of Hormuz sequence is a vigorous salt fountain, a crater clogged with insoluble debris, or a narrow (e.g. 25 km × 3 km) streak of coloured soils after a diapir has been smeared along a steep fault in the Sanandaj–Sirjan imbricate zone (Figs 2 and 8) depends on more than just the ratio of rates of salt rise and dissolution (Talbot & Jarvis 1984; Talbot 1993). Extrusive vigour is also likely to depend upon the thickness of the salt source (vigorous extrusions from thick sources) and its extrusion history. This is clear in the region around Bandar Abbas (Fig. 9) where salt extrusions still connected with their source layer act as gauges of tectonic pressure along the deep décollement. Topographies of salt extrusions emphasize a set of strike-slip faults that continue activity after the local arrival of the Zagros front but these are not considered further here (see Fürst 1976; Talbot 1992). Even where diapir topographies do vary systematically from south to north, as along the Kazerun and Mangarak fault zones (Fig. 5), the gradation is more likely to reflect tectonic history than rainfall. The closer a diapir is to the Zagros suture, the longer it has been reactivated or initiated by the arrival of the advancing Zagros thrusts and/or folds and the longer it has had to exhaust its deep source layer.

Influence of salt on Zagros folding in the Tertiary

The apparently haphazard relationship between salt diapirs and the Zagros folds is because most of the salt structures predate Zagros shortening in one form or another. Kent (1979) related emergent diapirs to Zagros folds in a designated part of Laristan and counted 13 diapirs as emergent on anticlinal culminations, 14 on anticlinal noses, eight on the flanks, two in synclines and left three unclassified.

What happens when the Zagros front eventually reaches any particular area depends on the nature of the salt structures already there. One of two things happens to already emergent diapirs. Where salt withdrawal has emptied the deep decollement, the resultant weld between the overburden and the basement pins the end of a future Zagros antiform (Kent 1979) or synform (Koyi 1988). All ten of the diapirs emergent in the southern gulf in front of the Zagros front are in synclines due to salt withdrawal (Kent 1979, fig. 9). Diapirs firmly pinned by welds become smeared along the thrusts that behead them (see Surmeh, top right on Fig. 5). These are unlikely ever to fountain and instead probably pass through a stage of being sub-circular breccia pipes before they are sheared to listric profiles and their planforms are squeezed to the ellipses elongate along the Zagros trend seen in the high Zagros (Koyi 1988).

Where sufficient autochthonous salt remains along the deep decollement, the advancing Zagros front rucks up deep, ridge-like salt mullions that may spawn a second suite of syn- or post-shortening diapirs (Koyi 1988).

In developing their thesis that most salt structures are triggered by (thin- or thick-skinned) extensional faulting, Jackson & Vendeville (1994) underplayed syn-shortening diapirism in the Zagros. Shortening was indeed irrelevant to the initiation of the pre-Zagros salt pillows, but not to the numerous cases where the Zagros front migrated along pre-Zagros salt pillows already aligned along the older transfer faults that became oblique footwall ramps during the Zagros orogeny. Deep pillows that had previously remained conformable, like those still on the platform, suddenly pierced and surfaced and contributed distinctive dark Hormuz clasts to the surrounding stratigraphy, which was characterized by pale colours (Kent 1979). Linear depotroughs deepened along or across the faults above the deflating pillows. In the Miocene, the Mangarak fault zone was the boundary between the Dezful gypsiferous facies to the NW and Razak (red-bed) facies of the Fars Group to the SE. This group thickens into a depotrough shared by both Kuh-e-Namak (Feroosabad) and Kuh-e-Jahani (Fig. 5) along the Mangarak fault zone (Kent 1979). Similarly, part of the Fars group also thickens into depocentres where NW trending Zagros thrusts swing into oblique footwall ramps along the Kazerun fault zone. Strong mutual feed-back between sedimentation and salt flow was increasingly delayed behind the Zagros front as it advanced southwestward. Pliocene siliciclastic deposits thicken to several times their usual thickness in the syncline south of a diapir along the Kazerun fault zone where a local 20° unconformity excising the Mishan Group records the deflation of the underlying pillow (Kent 1979). Similarly localized deposition resulting from the sudden deflation of a deep pillow is recorded by tilted Bahktyari conglomerates onlapping the crest of a fishtail anticline near the SW corner of Bachoon salt diapir (Fig. 5). Vast volumes of Hormuz salt that were extruded along the Kazerun and Mangarak fault zones in Miocene times were probably eroded and recycled as the salt in the Fars Group, which provided the shallow décollement responsible for such fishtail anticlines along the NW Zagros fold-thrust belt (O'Brien 1957, fig. 1).

Discussion

Tectonic pulse from formation and deformation of Hormuz salt

Rocks older than Jurassic are rarely exposed in the Zagros Simply Folded Belt and are deeply buried beneath the foreland. Consequently, the little we know of what happened near the Persian Gulf between the end of deposition of Hormuz salt in mid-Cambrian and the first documented salt movement in Jurassic comes from information in and near the diapirs.

Hormuz salt appears to have been restrained by the strength of its stiff carbonate overburden for *c.* 300 Ma (Kent 1958, Jackson & Vendeville 1994). Despite its positive buoyancy since early Palaeozoic burial, thickness and facies changes around the salt structures throughout the gulf region indicate that none started to rise until Jurassic or Early Cretaceous times. This pre-Zagros triggering of salt structures has been attributed to (Palaeo) Tethys beginning to close in the Jurassic (Kashfi 1976), to opening or closure of the NE trending Oman basin with its foredeep parallel to the Oman line (Alsharhan 1989), and to rift and drift of Neo-Tethys at some time between the Permian and earliest Cretaceous times (Jackson & Vendeville 1994). However, while attributing the earliest salt pillowing, piercement and most vigorous salt venting to regional extension of the north-dipping shelf during the opening of Neo-Tethys, Jackson & Vendeville (1994, p. 64) did not explain how salt pillows with N–S trends relate to N–S extension. Kent (1987, p. 31) considered the alignment of the salt structures at high angles to what later became the Zagros suture to demand an origin invoking tear rather than tension faults, and we agree with this view.

We consider both the closure of Paleo-Tethys in the Alborz mountains and the Early to Late Triassic opening of Neo-Tethys along what is now the Sanandaj–Sirjan imbricate zone to have been diachronous. However, we recognize no sign of either event in Zagros salt tectonics. Instead, we consider the most likely tectonic candidate for starting salt movement to have been the reactivation of basement blocks along the margin of Gondwana, which accompanied probable Jurassic subduction of ocean floor northward before the diachronous closure of Neo-Tethys along the Zagros suture began in the early Cretaceous.

Simultaneous opening or closure of a basin requires separation or rotation of large rigid blocks. Diachronous opening or closure of basins requires flexibility in the opposing sides. Basement blocks defined by old faults provide such flexibility. Zip fasteners engage or disengage rows of teeth that interlock along flexible borders; basins can open or close by strike-slip shuffling of teeth-like blocks that may not interlock so well when they close. Before disengagement or after opening, marginal basins of Tethys were like keyboards along which disturbances travelled as slow waves of vertical flexure (riffling). We will refer to basement blocks defined by transfer faults at high angles to the incipient marginal basins of Tethys as lithospheric keys. These 'lithospheric keys can be rifted and riffled, or drifted and riffled.

In Jurassic and Cretaceous times, we visualize diachronous zip-fastener-like subduction of Neo-Tethys as riffling the Gondwana keyboard along the subducting Arabian plate both before and after closure. We attribute initiation of the salt structures to local manifestations of subduction of Neo-Tethys before Zagros shortening of the sutured crust. Open-ocean subduction could account for the N-S alignment of pre-Zagros salt pillows and rows of pre-Zagros diapirs above the N–S edges of keys in an already segmented basement.

The way in which salt pillows have subsequently developed has depended on their distance from the Tethyan margin. Salt far to the south has remained conformable in deep salt pillows that grew slowly at nearly constant rates until the end of the lower Cretaceous (Edgell 1992, fig. 7). Diapirs closer to the unstable margin were more sensitive gauges of regional tectonic pressure. Spreads of distinctive dark Hormuz inclusions in the pale cover rocks record their extrusion in three main episodes: Lower Cretaceous, Eocene–Miocene and Recent. These episodes occurred when riffling of basement keys controlled depositional thicknesses and facies in the shallow marine sediments accumulating above them.

We now attempt to reconstruct the history of the region mainly using evidence brought up from depth with emergent salt. We start by using the inclusions in the salt to map its lithofacies.

Lithofacies of Hormuz sequence

Extrusive diapirs of the Hormuz sequence throughout the region rise through an indurated overburden consisting predominantly of carbonates. Only along the major transfer faults does a syn-Zagros cover sequence relate to local depotroughs, and only around some of the offshore islands were Tertiary shales sufficiently ductile to turn up in peripheral collars (Kent 1979, p. 121). Consequently, rather than inclusions in the Hormuz salt sampling the surrounding ductile overburden (as happens in diapirs downbuilt near the US Gulf coast: (Kupfer 1979)), the vast majority of inclusions in diapirs near the Persian Gulf were part of the original

Hormuz sequence (Kent 1958, 1970, 1979; Gansser 1960, 1992).

It has long been recognized that stromatolites and trilobites in different parts of the Hormuz sequence indicate ages ranging from late Neoproterozoic to mid-Cambrian. Until now there has been little attempt to discern details in the Hormuz story. However, our recent work on Zagros salt extrusions suggests that future mapping could distinguish not only Hormuz lithofacies but also divide an older from a younger Hormuz sequence. Here we sketch how such a division is possible in one area before tentatively extrapolating the distinction more broadly.

Kuh-e-Jahani (28°37′ N, 52° 25′ E) is the southernmost and currently the most voluminous salt extrusion along the Mangarak fault zone (Figs 5 & 6). The summit dome of this vigorous 11 km × 7 km oval salt fountain rises 1,485 m above sea-level. Five rings of different coloured soils trace funnel-shaped red layers concentric with both the distal flow front and the flanks of the summit dome (Kent 1958). The outer red layer consists of beds of red limestone and marl with a conformable breccia of black dolostone veined by sphalerite. We do not yet know the ages of the red layers, nor whether there is structural repetition among them. Nonetheless, they divide Kuh-e-Jahani into two portions. An outer periphery consists of distinctive grey and buff anhydritic soils (Fig. 8g). These are residual after halite that was cleaner and more uniform (Fig. 8f) than the multicoloured salt encircled by the red bands. Among the pale soils are numerous blocks of chloritic gabbro and vesicular, fine-grained diabase that are missing from other diapirs nearby.

Traction between salt diapirs and their country rocks turns the stratigraphies of their bedded source layers inside out within the diapir (Jackson & Talbot 1989). Stratigraphic inversion is usual beneath the axial surfaces of the 'tank-tracks' in salt diapirs spread near the surface (Fig. 7). The uniform soil residual after clean peripheral salt at Kuh-e-Jahani (Fig. 8g) is so different from elsewhere that Kent (1958) referred to it as a flow of mud-breccia. However, we interpret it as younger, purer allochthonous Hormuz succession encircling a core of multicoloured Hormuz sequence that is older.

Small volumes of late Hormuz sequence also occur around the peripheries of some of the other extrusions along the Mangarak fault zone. However, the significant volume of clean salt with igneous inclusions extruded at Kuh-e-Jahani is conspicuous by its absence, not only in the southernmost extrusion along the Kazerun fault zone 80 km to the SW, but also at the southernmost extrusion along the Mangarak zone only 6 km to the SW of Kuh-e-Jahani (Kent 1958). A strong facies boundary is implied between Jahani and Gach (Figs 5 and 6) in late Hormuz time, when both clean salt and mafic igneous activity appear to have been confined to a narrow trough now trending nearly N–S.

Early cyclic Hormuz sequence

What we interpret as the older (mainly Proterozoic?) Hormuz sequence at Kuh-e-Jahani and elsewhere along the Mangarak fault zone consists of thick beds of multicoloured salt and anhydrite (or their derivative soils) interbedded with dark foetid dolomites and thin red, purple or greenish sandstones, siltstones or marls (and some local yellow-brown orthoquartzites). These rock types generally match the autochthonous equivalent succession (without significant salt) on the Iranian plateau (Stöcklin 1968). The early Hormuz sequence is therefore typical of the Hormuz that contains huge rafts of bedded sediment exposed in most emergent diapirs in and near the Persian gulf, including Oman (Kent 1970). Abundant haematite, sulphur and local concentrations of base-metals indicate that the early Hormuz sequence accumulated in reducing conditions. The algal mats common in the dolostones indicate sabkha-type facies. These lithologies indicate that in early Hormuz times, an unknown number of cycles of salt, anhydrite and carbonate were deposited over large areas of shallow water with only local and temporary emergence. The early Hormuz was therefore cyclic like the Zechstein sequence of northern Europe (Kent 1979). Indeed, the Palaeozoic sequence throughout the region stayed shallow until Cretaceous turbidites indicate Stöcklin's (1968) seaway deepening along the current Sanandaj–Sirjan imbricate zone.

Late Hormuz sequence

The large volume of uniform grey or buff anhydritic salt at Kuh-e-Jahani is reminiscent of comparatively pure salt sequences like the Louann salt in the Gulf of Mexico. However, whereas the Louann salt covered a large region and is devoid of igneous inclusions, the uniform younger Hormuz salt near the Persian Gulf contains undated inclusions of chloritic gabbro and vesicular diabase and is noticeably more localized, like the Sedom salt of the Dead sea.

The Mangarak trough, which we infer to have deepened in late Hormuz times may have been confined to a half-graben as long (*c.* 200 km), narrow (12 km) and deep (1.5 km) as the Dead Sea basin, where the *c.* 1 km thick Sedom salt of Early Miocene age now rises in a line of three diapirs. Like the salt in the Dead Sea (Ben-Avraham *et al.* 1990), the clean late Hormuz salt in the Mangarak trough also accumulated in an isolated basin pulled

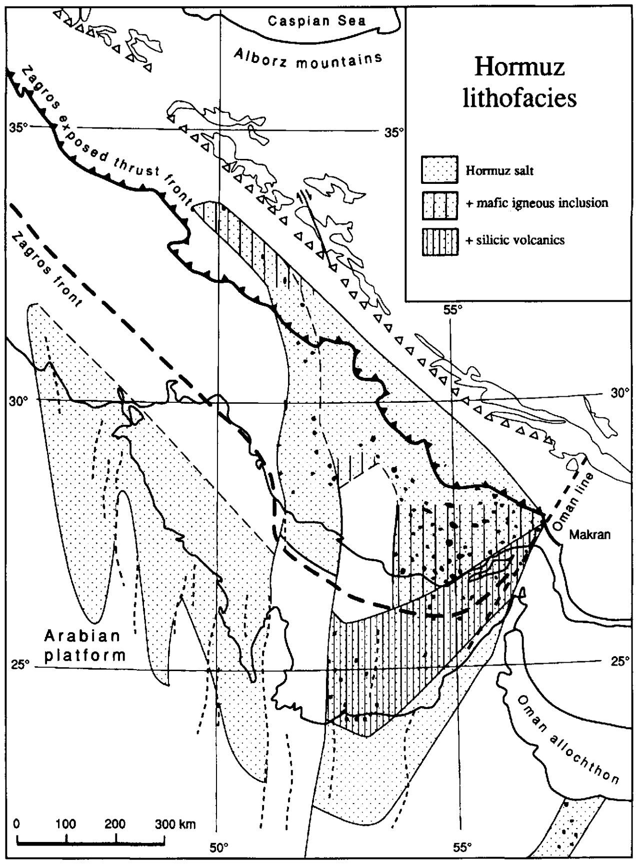

Fig. 10. Distinguishing Hormuz evaporite facies on the same basis as Figs 2 and 3 maps the basement keys under Proto-Tethys (based on Harrisson (1930), Kent (1958, 1970, 1979), Gansser (1960, 1993), Beydoun (1991) and Edgell (1992)). The basic assumption behind this map is that diapirs or pillows signal Hormuz salt of significant thickness while their absence implies insignificant salt thickness. Halite facies give way northward to dolomites of Hormuz-equivalent Soltanieh facies.

apart at a releasing bend along a plate-boundary fault inherited from the tectonic grain of its Pan-African basement. The main difference between these two rhombic basins was that strike-slip displacement was left-lateral along the Miocene Dead Sea and right-lateral along the late Hormuz Mangarak trough (Fig. 6).

Hormuz geography

The same subdivision of the Hormuz succession into cyclic early Hormuz and uniform later Hormuz that is possible at Kuh-e-Jahani may also be applicable to the Hormuz sequence elsewhere in the Zagros. Thus Kent (1987, p. 31) mentions a distinctive evaporitic and dolomitic unit overlying terrestrial siliciclastics in Chah Benu diapir (100 km north of the coast at 55.0° E). Gansser (1992, p. 837) emphasized that Kuh-e-Anguru (90 km ESE of Chah Benu) is devoid of significant inclusions. Indeed, many previous workers have alluded to two Hormuz sequences separated by a few hundred metres of carbonates and red beds (O'Brien 1957, Alsharhan 1989, Husseini & Husseini 1990; Beydoun 1991) but nobody has distinguished their palaeogeographies.

Because of dissolution, we cannot rely on previous descriptions of the salt itself to constrain early and late Hormuz geographies. Until the extrusions are remapped, only published reports of the igneous inclusions help limit the late Hormuz basins. This is because there are no igneous rocks in the regional cover above mid-Cambrian so that all the igneous inclusions were intrusive and extrusive into the Hormuz sequence (Kent 1979; Gansser 1992). The link we infer between igneous activity and uniform

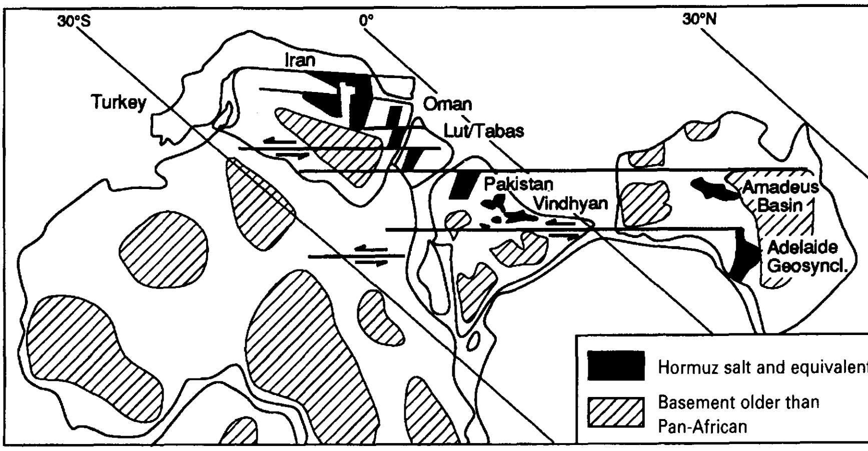

Fig. 11. Basins of Hormuz salt in Iran, Oman (Kent 1987), Lut-Tabas block (Stöcklin 1968), and equivalent sequences in Pakistan (Butler *et al.* 1987), the Vindhyan basin of India (Prasad 1984; Dey 1991) and Australia (Lindsay 1987; Kennedy 1993; Van der Bord, pers. comm. 1992). Neoproterozoic palaeolatitudes are from Scotese & McKerrow (1990).

clean salt is inevitably obscured, not only by dissolution but also by magma erupting in the pure younger Hormuz after having passed through the older cyclic Hormuz sequence. Descriptions of most individual diapirs merely list spilitic diabase as among 'the usual suite of Hormuz inclusions' (Harrisson 1930); they seldom mention whether the igneous and sedimentary inclusions are mutually exclusive as they certainly are at Kuh-e-Jahani. On the contrary, vulcanicity was not everywhere confined to otherwise clean salt, for Kent (1979, p. 125) mentioned mafic lavas or tuffs as being conformable in rafts of cyclic sediments at Chah Benu.

Despite all these qualifications, a surprisingly clear picture emerges (Fig. 10) from a careful re-reading of Harrisson (1930), Kent (1958, 1970, 1979, 1987) and Gansser (1992) leavened by our own limited field observations. Inclusions of intrusive diabase in diapirs in the Sanandaj–Sirjan imbricate zone and inland Laristan (Fig. 10) give way southward to extrusive mafic pillows and agglomerates along the coast (Kent 1958). By contrast, rhyolites, trachytes and porphyries are ubiquitous in the emergent diapirs forming the Gulf islands (Fig. 10). Silicic and mafic rocks occur together in only one diapir along the Iranian coast.

Igneous inclusions which are common at Kuh-e-Jahani are conspicuous by their positive absence to the north and west until they reappear 500 km away in the solitary salt diapir of Jebel-el-Sanan (Fig. 2) near the Iraq–Kuwait border (Kent 1970 p. 83). Igneous inclusions are also missing from the cyclic salt sequence in Oman except for some altered porphyries and rhyolitic tuffs in the southernmost emergent diapir (Kent 1987, p. 29).

The only exotic components in the Hormuz diapirs of Iran are very rare blocks of metamorphic rocks reported in extrusions near the southern coast. These are assumed to have fallen from fault scarps of basement during deposition (Kent 1979) or soon afterward (Alavi 1991a, b). Individual blocks of garnetiferous limestone, metamorphosed mudstone, schist, mafic mylonites, tonalite and a 3000 m^3 block of gneissic granite are listed by Kent (1979) and Gansser (1992). These are taken to be blocks of the Pan-African basement exposed in the Arabian–Nubian craton *c.* 800 km to the SW. Rocks with basement characteristics exposed in central Iran, west of the Tabas block (Fig. 1) and hidden deep beneath the Zagros, are also interpreted as Pan-African (Alavi 1991).

On a larger scale (Fig. 11), mafic intrusions occur in the Hormuz type sequence near Kerman (Stöcklin 1968). Butler *et al.* (1987, p. 354) do not mention igneous rocks among the red marls, gypsum and dolomites passing upward to gypsum and thick (630 m) salt with some potash in the Hormuz-equivalent Salt Range Formation in Pakistan. Basic tuffs and gypsum are reported in the cyclic shallow-marine and continental Neoproterozoic to Cambrian sequence (with pseudomorphs after halite at one level) forming rugged hills in the Vindhyan basin that inverted across northern India (Prasad 1984; Dey 1991). Igneous rocks appear to be missing from the shallow-marine cyclic Hormuz-equivalent successions containing salt in the Amadeus basin of central Australia

(Lindsay 1987, Kennedy 1993). However, igneous inclusions are present in the breccias which might indicate spreads of insoluble debris after extrusions of Hormuz-equivalent salt in the Adelaide geosyncline of south Australia (C. J. Van der Bord, pers. comm. 1992). Hormuz salt and equivalent sequences may have floored a broad tropical basin stretching from Australia through India, Pakistan and the Lut-Tabas block to Oman, with Iran being closest to a pole of spreading somewhere further to what is now the WNW (Fig. 11).

Proto-Tethys

Hormuz lithofacies boundaries in the Persian Gulf area (Fig. 10) have three main orientations: NW–SE, N–S and NE–SW. The NW trending boundaries define a basin that was parallel to later Tethyan basins along the margin of Gondwana and was sufficiently long, broad and shallow to be the likely repository of the early cyclic Hormuz sequence. In the absence of palaeomagnetic evidence for any significant ocean basin having opened near the Persian gulf in Hormuz times (Scotese & McKerrow 1990) we will adapt Kinsman's concept of a proto-ocean that failed to spread and refer to the Hormuz basin that rifted and riffled but failed to drift (Figs 10–12) as Proto-Tethys.

NW-trending boundaries of Proto-Tethys near the Persian Gulf are noticeably asymmetric (Fig. 10). Those to the SW are irregular (primary feather edges offset by faults?). Those to the NE (Fig. 12c) have smooth (fault?) traces and were probably controlled by the NW trending Najd strike-slip faults (Fig. 12b) in the Pan-African basement (Alsharhan 1989, Husseini & Husseini 1990). Proto-Tethys was segmented by cross-marginal troughs during the vulcanicity that accompanied accumulation of the younger Hormuz sequence (Fig. 12d). Abrupt edges of Hormuz lithofacies, which now trend N–S and NE–SW bound blocks that parallel and were almost certainly inherited from, the *c.* 1000–600 Ma old terrain-accretion fabric (Fig. 12a) that preceded the Najd faults in the Pan-African basement (Alsharhan 1989). The lithospheric keyboard riffled by the mantle beneath the younger Hormuz basins also appears on regional maps of isopachs of Permo-Carboniferous strata above the Hercynian unconformity (Eyles 1993, fig. 16.19) and free air gravity anomalies and aeromagnetic maps described by Edgell (1992).

Proto-Tethys rifting and riffling but not drifting

Instead of Proto-Tethys opening to an ocean, the basement keyboard ceased to play at about the stage where the lithosphere had rifted and riffled but not drifted). The keys along the edge of Gondwana were stilled and buried beneath Cambrian to Lower Ordovician carbonates and clastic sediments with no sign of any local volcanics (Figs 12d and 12e). Proto-Tethys was still-born when igneous activity migrated to open Palaeo-Tethys further to the north (Figs. 12d and 12e). Huge volumes of mid-Ordovician to mid-Devonian mafic to intermediate intrusive and extrusive igneous rocks occur in the Zagros imbricate zone, central Iran and the Alborz mountains: these are taken to record the opening of Palaeo-Tethys because they are neither metamorphosed nor deformed by either subduction or orogeny (Sengor & Burke 1978).

Husseini & Husseini (1990, fig. 5) appear to have attributed the Hormuz basins in the Persian Gulf region to aborted spreading ridges trending NE, being offset along Najd transform faults now trending NW. However, impressed by the Mangarak trough and Fig. 9, we agree with Stamfli *et al.* (1991) and reverse these kinematics, thinking of the aborted rifts as now trending NW with potential transforms faults now trending NE.

The width and complexity of the crust stretched beneath the present Persian Gulf suggested to Hempton (1987) that the whole of the north Arabian continental margin was on the lower plate or footwall when Palaeo-Tethys eventually opened in Ordovician time by simple extensional lithospheric shear to the N or NE. This may be so, but the lithospheric keys along the zip fastener that failed to open Proto-Tethys (Fig. 10) add earlier details to the saga that began with Proto-Tethys and continues even now with the Red Sea (Fig. 12).

We do not think of Proto-Tethys as an aulacogen, a rift inland of a continental margin where one branch of a triple rift junction failed to drift to an ocean. Instead we rationalise the still-birth of the half-graben of Proto-Tethys (Fig. 12d) in terms of a model of lithospheric extension by simple shear (Wernicke 1985; Stamfli *et al.* 1991; Hempton 1987; Brun *et al.* 1994). The order in which rifting was followed by early Hormuz salt deposition, and then uplift and volcanism along late Hormuz insert basins, implies passive rather than active rifting (Sengör & Burke 1978).

The thick sedimentary cover on the broad gentle shelf on the SW side of Proto-Tethys in Iran is symptomatic of a footwall of a basin in lithosphere extended by simple shear (Figs 10–12). Hormuz salt has insignificant thickness on the narrow shelves on the opposing hanging wall. The incipient Qatar syntaxis and Fars platform were defined by the only transfer faults that reversed the general asymmetry. To prime the future syntaxis, two particular lithospheric keys went up rather than down, perhaps because two strips of the Pan-African basement had distinctive characters.

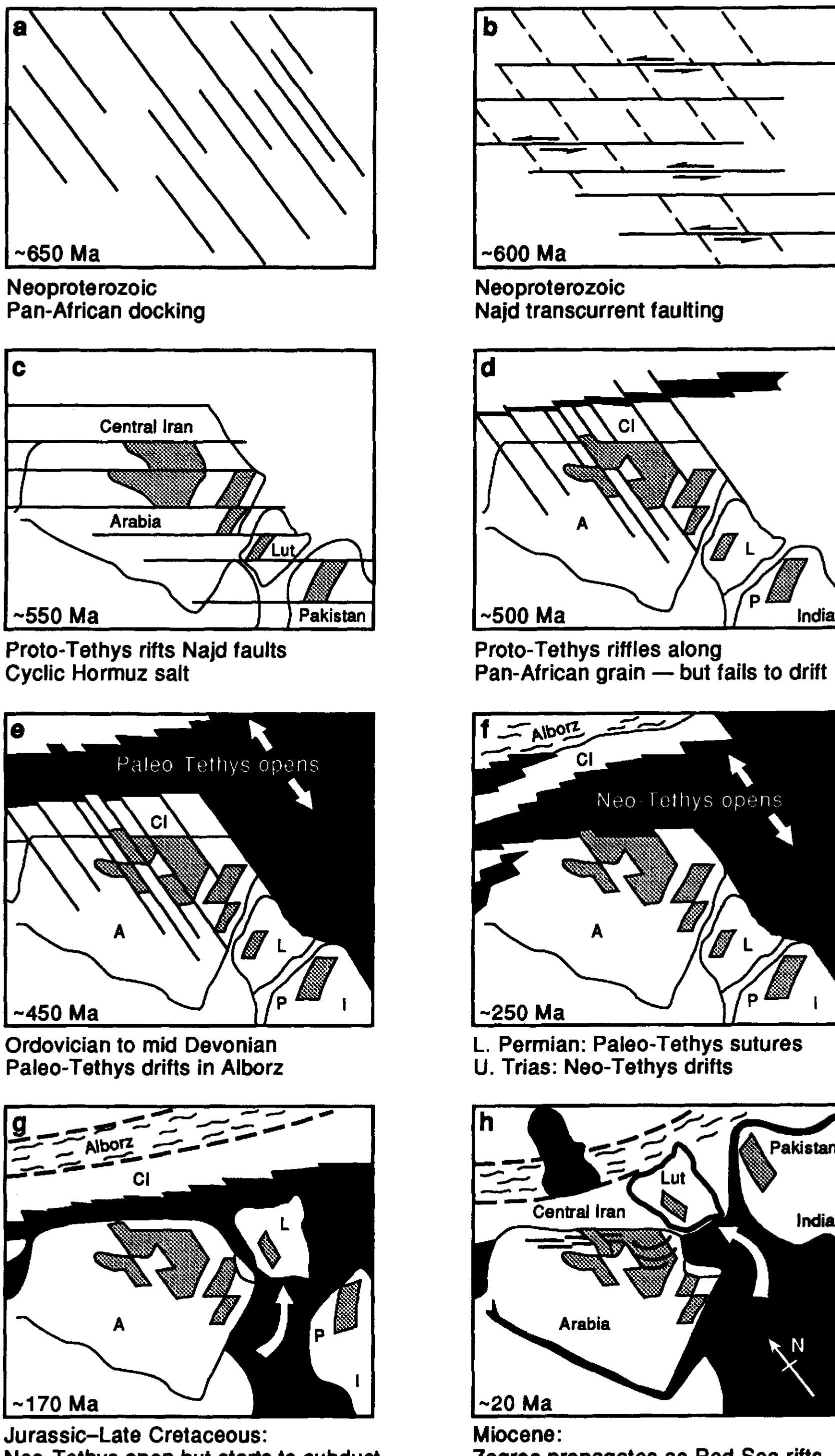

Fig. 12. Tethyan basins have been opening and closing like zip fasteners along the margin of Greater Gondwana since the Pan-African orogeny brought east and west Gondwana together. The Red Sea is just the latest in a long list of Tethyan basins.

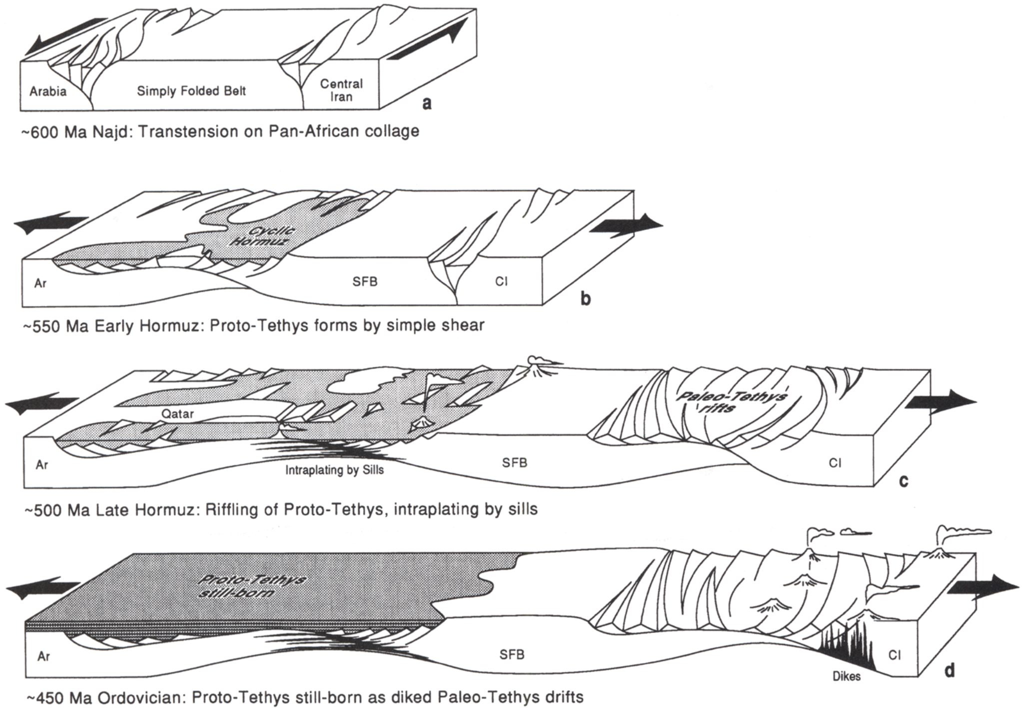

Fig. 13. Proto-Tethys may have rifted when a flower structure along a Najd strike-slip fault matured to an initial breakaway. The Arabian plate riffled and most of it subsided as slow extension pulled it off the passively bulging asthenosphere. Qatar became an incipient syntaxis because it rose on a hangingwall between the Kazerun–Qatar and Mangarak–Marzuk transfer faults. Proto-Tethys may have failed to drift because lower Cambrian intraplating involved sills. Palaeo-Tethys may have rifted and drifted further north because it involved dykes (adapted from Wernicke (1985); Hempton (1987), Stamfli *et al.* (1991) and Brun *et al.* (1993)).

We follow Husseini & Husseini (1990) and interpret the smooth NW trending boundary along the NE side of Proto-Tethys to have initiated as a steep strike-slip Najd fault (Fig. 13a). We assume that this steep fault rotated to become the master fault along which most of the slow ductile N–S extension of Proto-Tethys occurred (Fig. 13b). We infer that this master fault dipped northward under the NW Zagros fold-thrust belt and the SE Zagros fold-diapir festoon, but southward under the Qatar arch and the Fars platform (Fig. 12). Slow lithospheric extension pulled the Iranian hangingwall off the (passive or reactive) isostatically bulging asthenosphere. The active main detachment fault remained steep to the NE but was progressively deactivated to the SW as it was rotated to a listric accommodation fault (Brun *et al.* 1994) with gentle dips on the shoulder of the Arabian footwall (Fig. 13c). The many basin-parallel faults anticipated by this model are assumed to be buried beneath the post-rift early Hormuz cyclic salt in which the lithofacies map two depotroughs, a hanging wall half-graben bound to the north by the main detachment fault, and an older footwall basin with a southern edge bound by the inactivated listric accommodation fault (Fig. 13c).

We infer from the pattern of igneous activity between the Mangarak–Marzuk fault zone and Oman syntaxis that mafic intraplating melted the deepest N-dipping Arabian footwall and led to silicic melts erupting to the south (Fig. 13c). Mafic sills are more efficient than dykes at heating and softening continental crust, but less efficient at disrupting the lithosphere. We infer that the slow extensional rifting of Proto-Tethys failed in mid-Cambrian because the passively bulging asthenosphere intruded sills rather than dykes (Fig. 13c). Palaeo-Tethys was opened by Ordovician to mid-Devonian dykes further north (Fig. 13d).

Because Proto-Tethys rifted and riffled but failed to drift to an ocean, it became a remarkably successful hydrocarbon kitchen where the extraordinary hydrocarbon riches in and beside the current Persian Gulf were brewed and trapped. This is because the still-born ocean settled to a long and extraordinarily wide, almost flat-bottomed, shallow epeiric shelf-sea on the passive margin of

Gondwana until the late Palaeozoic (Beydoun 1991, p. 19). The NE margin of this 2000 km wide shelf was marked by continental magmatism and the accumulation of siliciclastic red-beds in the Sanandaj–Sirjan zone during Silurian, Devonian and Carboniferous times (Alavi 1991).

Late Permian rifting and Upper Triassic drifting (Beydoun 1991, p. 19) further shredded the margin of Gondwana when Neo-Tethys started to open westward, like a zip fastener, along what is now the Zagros imbricate zone (Fig. 12f). The closure of Palaeo-Tethys soon afterwards (Fig. 12f) is recorded by a magmatic arc (or ophiolites) along the suture in the Alborz mountains (Alavi, in review). The diachronous zipping open (Fig. 12f) and closure (Fig. 12g) of NeoTethys is recognisable in the age of the oil and gas reservoirs which young from Jurassic in the west to middle Cretaceous in the east. Later, as the Zagros front arrived in each area, oil either escaped or remigrated into Asmari reservoirs that were sealed by the Miocene evaporitic sequence and folded by Zagros shortening (Dunnington 1967).

The facies boundaries defining the keys in the Tethyan margin of Gondwana beneath the Gulf extrapolate southward along small circles across the whole of the Arabian platform to transform faults in the spreading ridges of the Gulf of Aden and Red Sea, which rifted 25 Ma BP in the Miocene (Fig. 12h) and began drifting at 5 Ma BP. The most significant lithospheric key along the Zagros, the incipient Qatar syntaxis, is on the same small circle as the dog-leg between the Red Sea and the Gulf of Aden. It is also in line with, and much the same width as, the Ethiopian rift valley. Such relationships raise the possibility that transform margins in the current spreading ridge were guided by the same old lines of weakness built into the basement by the Pan-African orogeny. This would make the Red Sea merely the present installment of the saga that began with Proto-Tethys riffling the keys along Najd faults in the Pan-African basement in late Proterozoic times.

Conclusions

The mantle is still playing the same keyboard in the Tethyan margin of the African and Arabian plates that was constructed by Pan-African docking and diced by Najd faults. Some keys played more important roles than others during each glissand or riffle along the lithospheric keyboard. The incipient Qatar syntaxis assumed particular importance after it went up rather than down along the margin of Proto-Tethys in about mid-Cambrian times. The key destined to become a syntaxis perhaps 20 Ma in the future was chosen *c.* 500 Ma in the past, when it rose too high for Hormuz salt to survive on it.

Salt deposited on the depressed keys did not influence the distant opening or closure of Palaeo-Tethys, but strongly influenced subsequent suturing and shortening in the Zagros. A deep décollement of salt amplified the style of rifting, drifting and closure of Tethyan ocean basins and strongly influenced the style of riffling and shortening of sutured continental crust. The hydrocarbon fields of the region are huge because Proto-Tethys aborted to a flat shallow shelf that jostled only gentle when various Tethyan basins opened further north. This gentle riffling was sufficient to collect impressive quantities of hydrocarbons in periclines draped over the deep salt pillows that map the edges of the lithospheric keys, but not enough to drift Proto-Tethys to an ocean.

The Kazerun–Qatar and Mangarak–Marzuk lineaments were first introduced as part of a keynote talk at the Salt Tectonics meeting of the combined Petroleum and Tectonics Groups of the Geological Society of London on 14–15 September 1994.

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References

ALA, M. A. 1974. Salt diapirism in southern Iran. *AAPG Bulletin*, **58**, 1758–1770.

ALAVI, M. 1991a. Sedimentary and structural characteristics of the Paleo-Tethys remnant in northeastern Iran. *Bulletin of the Geological Society of America*, **103**, 983–992.

—— 1991b. Tectonic map of the Middle East (at scale 1:5,000,000). *Geological Survey of Iran, P.O. Box 13185-1494, Tehran, Iran,*

—— 1992. Thrust tectonics in the Bidalood region: NE Iran. *Tectonics*, **11**, 360–370.

—— 1994. Tectonics of the Zagros orogenic belt of Iran: new data and interpretations. *Tectonophysics*, **229**, 211–238.

ALSHARHAN, A. S. 1989. The petroleum geology of the United Arab Emirates. *Journal of Petroleum Geology*, **12**, 253–288.

BAKER, C, JACKSON, J. A. & PRIESTLY, K. 1993. Earthquakes on the Kazerun line in the Zagros mountains of Iran: strike-slip faulting within a fold-thrust belt. *Geophysical Journal International*, **115**, 41–61.

BEN-AVRAHAM, Z., TEN BRINK, U. & CHARRACH, J. 1990. Transverse faults at the northern end of the southern basin of the Dead sea graben. *Tectonophysics*, **180**, 37–47.

BEYDOUN, Z. R. 1991, *Arabian Plate Hydrocarbon*

Geology and Potential – a Plate Tectonic Approach. American Association of Petroleum Geologists Studies in Geology, **33**.

BRUN, J-P., SOKOUTIS, D. & VAN DEN DREISCHE, J. 1994. Analogue modelling of detachment fault systems and core complexes. *Geology*, **22**, 319–322.

BUTLER, R. W. H. COWARD, M. P. HARWOOD, G. M. & KNIPE, R. J. 1987. Salt control on thrust geometry structural style, and gravitational collapse along the Himalayan front in the Salt Range of northern Pakistan *In*: LERCHE, I. & O'BRIEN, J. J. (eds) *Dynamical Geology of Salt and Related Structures.* Academic, New York, 301-337.

DAVIS, D. M. & ENGLEDER, R. 1987. Thin-skinned deformation over salt. *In*: LERCHE, I. & O'BRIEN, J. J. (eds) *Dynamical Geology of salt and related structures.* Academic, New York, 301–337.

—— & LILLIE, R. 1994. Changing mechanical response during continental collision: active examples from the foreland thrust belts of Pakistan. *Journal of Structural Geology*, **16**, 21–34.

DEY, R. C. 1991. Trans-Aravalli Vindhyan evaporites under the semi-desertic plains of western India; significance of depositional features. *Quarterly Journal of the Geological, Mining and Metallurgical Society of India*, **37**, 136–150.

DUNNINGTON, H. V. 1967. Stratigraphic distribution of oilfields in the Iraq–Iran–Arabia basin. *Journal of the Institute of Petroleum*, **53**, 129–161.

DYKSTRA, J. D. & BIRNIE, R. W. 1979. Segmentation of the Quarternary subduction zone under the Baluchistan region of Pakistan and Iran, *In*: FARAH, A. & DE JONG, K. A. (eds) *Geodynamics of Pakistan.* Geological Survey of Pakistan, Quetta, 319–323

EDGELL, H. S. 1992. Basement tectonics of Saudi Arabia as related to oil field structures. In: RICKARD, M. J. *et al.* (eds) *Basement Tectonics.* Kluwer, Dordrecht, 169–193.

EKSTRÖM, G. & ENGLAND, P. 1989. Seismic strain rates in regions of distributed continental deformation. *Journal of Geophysical Research*, **94**, 10231–10257.

EYLES, N. 1993. Earth glacial record and its tectonic setting. *Earth Science Reviews*, **35**, 3–150.

FÜRST, M. 1976. Tektonic und diapirismus der östeerlichen Zagrosketten. *Zeitschrift der Deutschen geologischen Gesellschaft*, **127**, 183–225.

GANSSER, A. 1960. Über Schlammvulkane und Saklzdome. *Viertejahrsschrift der Naturforschenden Gersellschaft i Zürich*, **105**, 1–46.

—— 1992. The enigma of of the Persian dome inclusions. *Eclogae Geologica Helveticae*, **85**, 825–846.

GERA, F. 1972. Review of salt tectonics in relation to disposal of radioactive wastes in salt formation. *AAPG Bulletin*, **83**, 3551–3574.

GUSSOW, W. C. 1966, Salt temperature: a fundamental factor in salt dome intrusion. *Nature*, **210**, 518–519 (and reply to discussion: *Nature*, **211**, 1387–1388).

HARRISON, J. V. 1930. The geology of some salt-plugs in Lariistan (southern Persia). *Quarterly Journal of the Geological Society, London*, **86**, 463–522.

HEATON, R., JACKSON, M. P. A., BAMAHOUD, M. & NANI, A. S. O. (in press). Superposed Neogene extension, contraction and salt canopy emplacement in the Yemeni Red Sea. *In*: JACKSON, M. P. A., ROBERTS, D. G. & SNELSON, S. (eds) *Salt Tectonics: A Global Perspective for Exploration.* American Association of Petroleum Geologists, Memoir.

HEMPTON, M. R. 1987. Constraints on Arabian plate motion and extensional history of the Red Sea. *Tectonics*, **6**, 687–705.

HUSSEINI, M. I. 1989. Tectonic and depositional model of late Precambrian–Cambrian Arabian & adjoining plates. *AAPG Bulletin*, **73**, 1117–1131.

—— & HUSSEINI, S. I. 1990. Origin of the Infracambrian salt basins of the middle East *In*: BROOKS, J. (ed.) *Classic Petroleum Provinces.* Geological Society, London, Special Publication, **50**, 279–292.

JACKSON, J. A. & MCKENZIE, D. P. 1988. The relationship between plate motions and seismic moment tensors and the rates of active deformations in the Mediterranean and the Middle East. *Geophysical Journal of the Royal Astronomical Society*, **93**, 45–73.

—— & TALBOT, C. J. 1989. Anatomy of mushroom-shaped diapirs. *Journal of Structural Geology*, **11**, 211–230.

—— & VENDEVILLE, B. C. 1994. Regional extension as a geologic trigger for diapirism. *Bulletin of the Geological Society of America*, **106**, 57–73.

KASHEI, M. S. 1976. Plate tectonics and structural evolution of the Zagros geosynclines, southwestern Iran. *Bulletin of the Geological Society of America*, **87**, 1486–1490.

KENNEDY, M. J. 1993. The Undoolya Sequence; a new stratigraphic unit syn-depositional adjacent to a late Proterozoic salt structure; Amadeus Basin, Central Australia. *Australian Journal of Earth Science*, **106**, 57–73.

KENT, P. E. 1958. Recent studies of south Persian salt plugs. *AAPG Bulletin*, **422**, 2951–2972.

—— 1970. The salt plugs of the Persian Gulf region. *Transactions of the Leicester Literary & Philosophical Society*, **64**, 56–88.

—— 1979. The emergent Hormuz salt plugs of southern Iran. *Journal of Petroleum Geology*, **2**, 117–144.

—— 1987. Island salt plugs in the middle east and their tectonic implications. *In*: LERCHE, I. & O'BRIEN, J. J. (eds) *Dynamical Geology of salt and related structures.* Academic, New York, 3–37.

KOYI, H. 1988. Experimental modeling of role of gravity and lateral shortening in Zagros mountain belt. *AAPG Bulletin*, **72**, 1381–1394.

KUPFER, D. H. 1979. Internal kinematics of salt diapirs: Discussion. *AAPG Bulletin*, **73**, 939–942.

LETOUZEY, J. COLLETA, B., VIALLY, R. & CHERNETTE, J. C. (in press). Evolution of salt-related structures in compressional settings. *In*: JACKSON, M. P. A., ROBERTS, D. G. & SNELSON, S. (eds) *Salt Tectonics: A Global Perspective for Exploration.* American Association of Petroleum Geologists, Memoir.

LINDSAY, J. F. 1987. Upper Proterozoic evaporites in the Amadeus basin, central Australia and their role in basin tectonics. *Bulletin of the Geological Society of America*, **99**, 852–865.

O'BRIEN, C. A. E. 1957. Salt diapirism in south Persia. *Geologie en Mijnbouw, Nieue Serie*, **19**, 357–376.

PRASAD, B. 1984. *Review of Vindhyan Supergroup of SE Rajasthan.* Geological Survey of India Miscellaneous publications, **50**, 31– 40.

SARWAR, G. & DE JONG, K. A. 1979. Arcs, oroclines, syntaxes: The curvature of mountain belts in Pakistan. *In*: FARAH, A. & DE JONG, K. A. (eds) *Geodynamics of Pakistan*. Geological Survey of Pakistan, Quetta, 341–349.

SCHWERDTNER, W. N. & OSADEZ, K. 1983. Evaporite diapirism in the Sverdrup basin: New insights and unsolved problems. *Bulletin of Canadian Petroleum Geology*, **31**, 27–36.

SCOTESE, C. R. & MCKERROW, W. S. 1990. Revised world maps and introduction. *In*: MCKERROW, W. S. & SCOTESE, C. R. (eds) *Palaeogeography and Biogeography*. Geological Society, London, Memoir **12**, 1–21.

SENGÖR, A. M. C. & BURKE, K. 1978. Relative timing and volcanism on Earth and its tectonic implications. *Geophysical Research Letters*, **5**, 419–421.

STAMFLI, G., MARCOUX, J. & BAUD, A. 1991. Tethyan margins in space and time. *Paleogeography, Palaeoclimatology & Palaoecology*, **87**, 373–409.

STÖCKLIN, J. 1968. *Salt Deposits of the Middle East*. Geological Society of America, Special Paper, **88**, 158–181.

TALBOT, C. J. 1979. Fold trains in a glacier of salt in southern Iran. *Journal of Structural Geology*, **1**, 5–18.

—— 1992: *Quo Vadis* Tectonophysics? with a pinch of salt! *Journal of Geodynamics*, **16**, 1–20.

—— 1993. Spreading of salt structures in the Gulf of Mexico. *Tectonophysics*, **228**, 151–166.

—— & JARVIS R. J. 1984. Age, budget and dynamics of an active salt extrusion in Iran, *Journal of Structural Geology*, **6**, 521–533.

—— & ROGERS, E. A. 1980. Seasonal movements in a salt glacier in Iran. *Science*, **208**, 395–397.

——, KOYI, H., SOKOUTIS, D. & MULUGETA, G. 1987. Identification of diapirs formed in horizontal compression. *Bulletin of Canadian Petroleum Geologists*, **36**, 91–94.

URAI, J. L., SPIERS, C. J. ZWART, H. J. & LISTER, G. S. 1986. Weakening of rock salt by water during long term creep. *Nature*, **324**, 554–557.

WEINBERG, R. F. 1993. The upward transport of inclusions in Newtonian and power-law salt diapirs. *Tectonophysics*, **228**, 141–150.

WERNICKE, B. 1985. Uniform-sense normal simple shear of the continental lithosphere. *Canadian Journal of Earth Sciences*, **22**, 108–125.