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# The eastern termination of the Zagros Fold-and-Thrust Belt, Iran: Structures, evolution, and relationships between salt plugs, folding, and faulting

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[1] The Zagros Mountains result from the ongoing collision between the Arabian and central Iran plates. The main features of the eastern Zagros are (1) numerous emerged or buried salt diapirs, made up of Late Precambrian Hormuz salt and (2) the irregular along-strike shape of the collision-related detachment folds with frequent bending. To understand this layout, four geological cross sections have been constructed from the Persian Gulf foreland basin to the inner part of the Zagros Fold-and-Thrust Belt. Shortening in the deformed parts of the sections is less than 10% and is mainly accommodated by detachment folding. We show that late Cenozoic folding occurred in a region that was already punctuated by salt domes and diapirs. In fact, almost continuous halokinesis developed since the earlier Paleozoic, i.e., just short time after the deposition of the Hormuz salt, and continued up to the Present. These preexisting salt structures and their relevant local thickening strongly influenced both the localization and the direction of folds. **Citation:** Jahani, S., J.-P. Callot, J. Letouzey, and D. Frizon de Lamotte (2009), The eastern termination of the Zagros Fold-and-Thrust Belt, Iran: Structures, evolution, and relationships between salt plugs, folding, and faulting, *Tectonics*, 28, TC6004, doi:10.1029/2008TC002418.

## 1. Introduction

[2] The Zagros Fold-and-Thrust Belt (ZFTB), a part of the Alpine-Himalayan orogenic belt, is located in the northern part of Arabian plate. Situated at the eastern tip of the ZFTB (southern Fars Province and Bandar Abbas hinterland) and Persian Gulf (Figure 1), the study area is situated at the junction of three geological systems namely: the Zagros Mountains, the Makran accretionary prism and the Oman Mountains. Compared to other parts of the Zagros, the eastern Zagros presents two main characteristics:

[3] 1. Numerous emerged or still buried salt diapirs (plugs and domes), distributed irregularly in a wide region from the suture zone in the north to the Persian Gulf in the south (Figures 1 and 2) and playing a major role in the tectonic history of this area [e.g., *Jahani et al.*, 2007].

[4] 2. Particular aspect ratios (half wavelength/axial length) of folds, which, compared to other parts of the Zagros, are short “compact” folds with irregular along strike shapes rather than “long and thin” and asymmetric [*Sattarzadeh et al.*, 1999; *Blanc et al.*, 2003; *Molinaro et al.*, 2004, 2005b; *Sherkati and Letouzey*, 2004; *Sherkati et al.*, 2005, 2006; *Sepehr and Cosgrove*, 2005; *Sepehr et al.*, 2006]; they frequently show “dog legs” (or zigzag like) shape on maps with important changes of the fold axis trends (Figure 2).

[5] Recent studies [*Molinaro et al.*, 2004, 2005a, 2005b; *Leturmy et al.*, 2009] focus mainly on the kinematic evolution of the southeastern Zagros and the role and timing of basement faulting with respect to thin-skinned shortening. For this purpose, *Molinaro et al.* [2005a] used geological mapping and a general N–S balanced cross section mainly built on the basis of field data. On the other hand, *Leturmy et al.* [2009] present a combined morphological and structural analysis of basement faults and their impact on the river network. These studies do not deal with salt tectonics and, in particular, the time and space relationships between the salt diapirs, folding, and faulting.

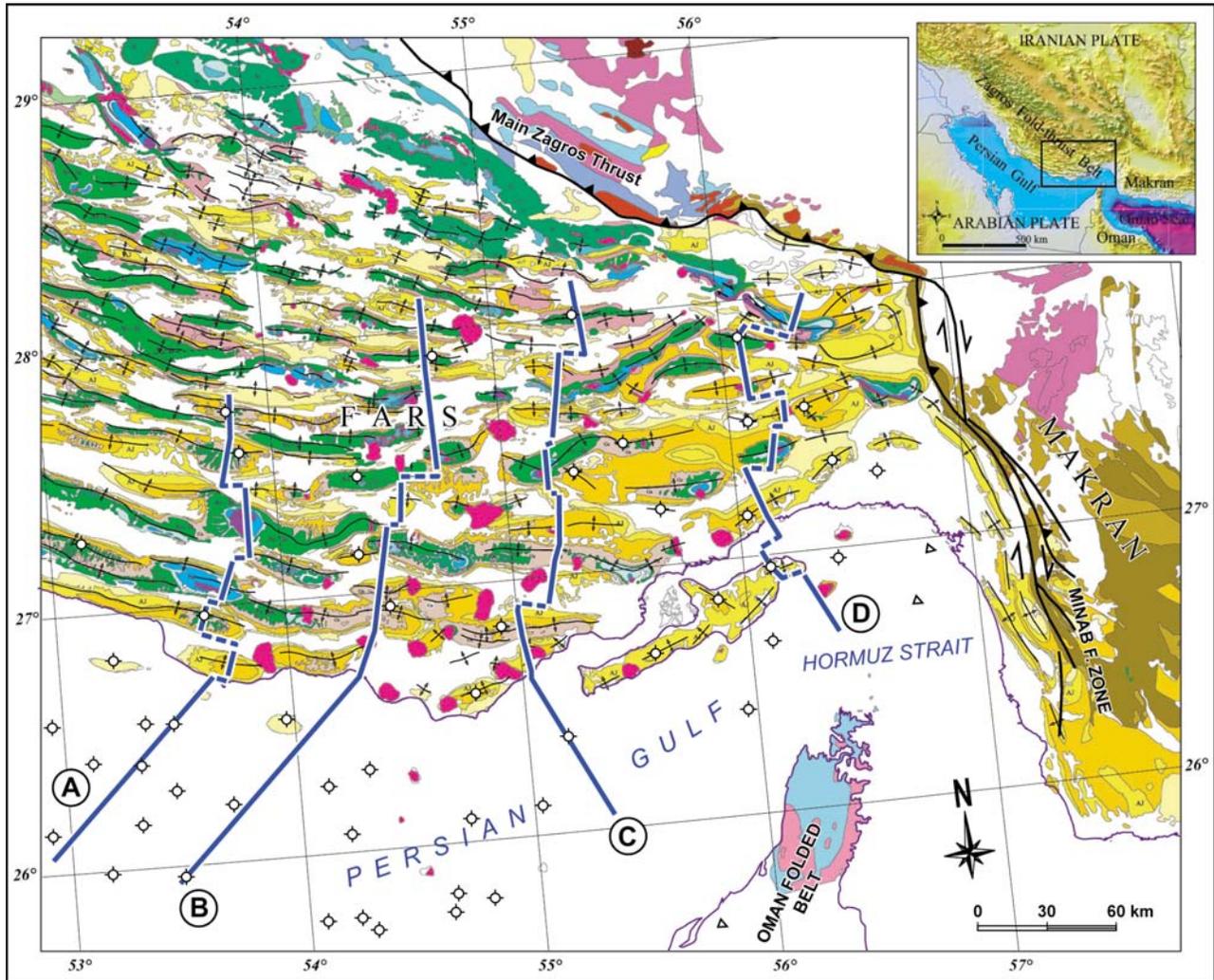
[6] Emergent salt diapirs exist in various parts of the Zagros and in the Southern Persian Gulf [*Harrison*, 1930; *Kent*, 1958, 1970; *Edgell*, 1996; *Talbot and Alavi*, 1996; R. A. Player, Salt diapirs study, unpublished report 1146, National Iranian Oil Company, NIOC Exploration, Tehran, 1969]. In central Zagros, they seem directly related to tear or thrust faults [*Talbot and Alavi*, 1996; *Letouzey and Sherkati*, 2004; *Koyi et al.*, 2008]. *Letouzey et al.* [1995] and *Vendeville and Nilsen* [1995] established that contraction triggers episodic rise of previously inactive diapirs, forcing salt upward. On the basis of the results of analog experiments and field observations in the central Zagros provinces, *Letouzey and Sherkati* [2004] deduced that thrust and wrench faults are often controlled by the presence of preexisting salt domes. In contrast, only few emergent diapirs are directly related to tear or thrust faults in the southeastern Zagros (Figure 2) [*Jahani et al.*, 2007; *Callot et al.*, 2007].

[7] The initiation of salt movement and the emplacement pattern of the emergent salt domes has been first considered to be related to basement structures [*Haynes and McQuillan*, 1974; *Kent*, 1987; *McQuillan*, 1991; *Edgell*,

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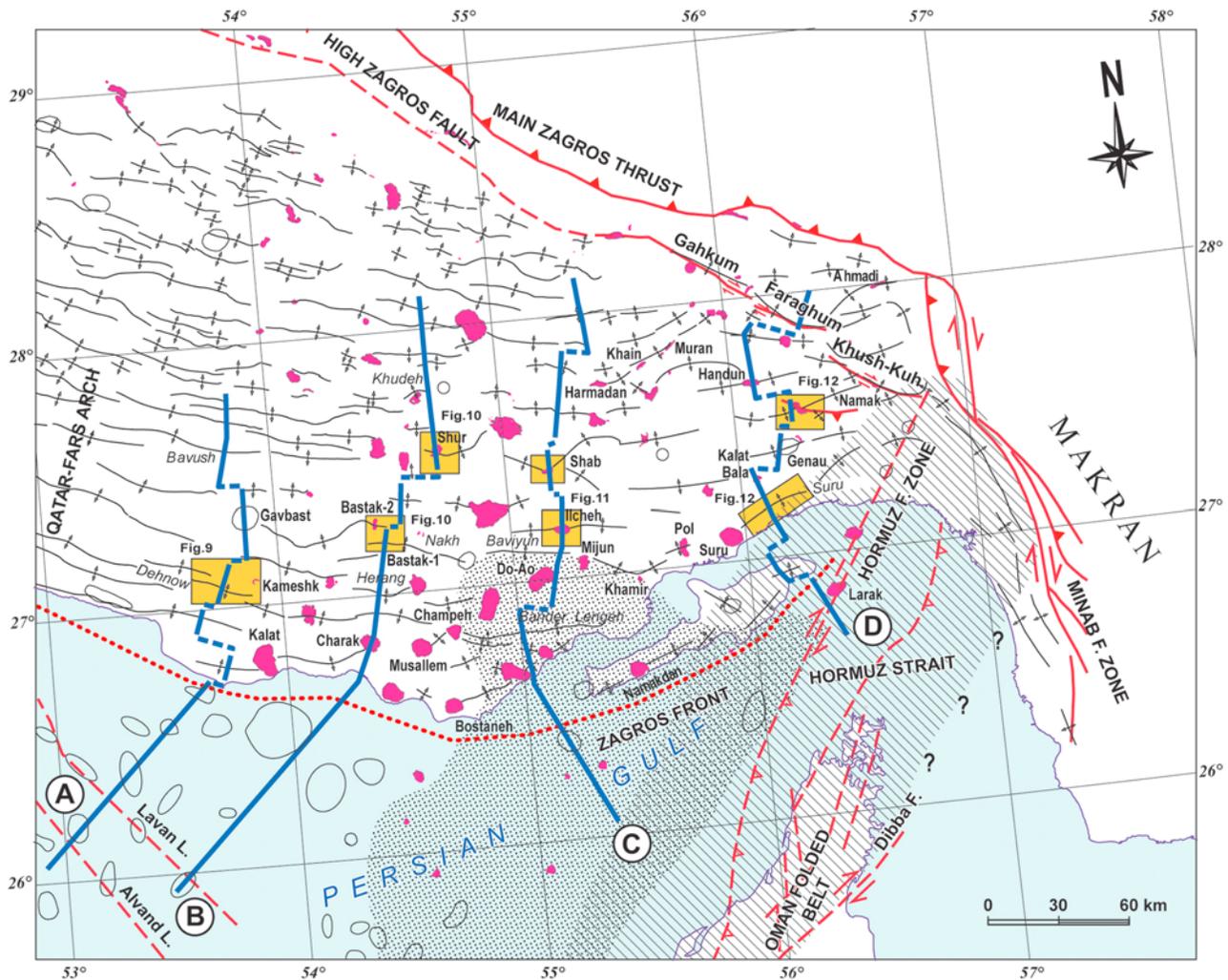
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**GEOLOGICAL LEGEND**

| ZAGROS |   |   |    |    | CENTRAL IRAN AND MAKHRAN |    |    |    |    |    |    |
|--------|---|---|----|----|--------------------------|----|----|----|----|----|----|
| 1      | 4 | 7 | 10 | 13 | 16                       | 19 | 21 | 22 | 24 | 26 | 28 |
| 2      | 5 | 8 | 11 | 14 | 17                       | 20 | 23 | 25 | 27 | 29 |    |
| 3      | 6 | 9 | 12 | 15 | 18                       |    |    |    |    |    |    |

**Figure 1.** Geological map of the eastern Zagros Fold-and-Thrust Belt (ZFTB) (Fars and Bandar-Abbas hinterland) compiled from National Iranian Oil Company (NIOC) unpublished 1,000,000 scale geological map, with location of the regional cross sections (Figure 8) and wells used in this study. Main salt diapirs and major structural elements are shown in magenta color and black lines, respectively. (1) Pleistocene (Bakhtyari), (2) Pliocene (Aghajari), (3) mid-Miocene (Guri-Mishan), (4) Neogene (Fars Group), (5) early Miocene (Razak), (6) early Miocene (Gachsaran), (7) late Oligocene–early Miocene (Asmari), (8) Paleogene–early Miocene (Asmari-Jahrum), (9) Paleogene (Jahrum), (10) Paleogene (Pabdeh), (11) Maastrichtian (Tarbur), (12) Late Cretaceous (Gurpi), (13) Late Cretaceous–Paleogene (Pabdeh-Gurpi), (14) Mid-Cretaceous (Bangestan Group), (15) Late Jurassic (Hith-Surmeh), (16) Late Jurassic–Early Cretaceous (Khami group), (17) Triassic (Kangan, Dashtak–Khane-kat, (18) Late Paleozoic, (19) Early Paleozoic, (20) Late Precambrian–Early Cambrian (Hormuz salt), (21) Paleogene (Makran Flysch), (22) early Paleogene (flysch-ultrabasics-ophiolites), (23) Late Cretaceous–early Paleogene (Colored Melange), (24) Late Cretaceous (Radiolarite group), (25) Mesozoic, (26) Jurassic–Cretaceous, (27) Jurassic–Cretaceous, (28) Jurassic, (29) Paleozoic.



**Figure 2.** Structural map of the eastern Zagros and the south Persian Gulf showing the front of the Zagros folding and the distribution of fold axes; the buried northern prolongation of the Oman Folded Belt, with the extension of the mid-Miocene unconformity above Oman Mountains structures below the Hormuz strait (oblique line zone); the extension of the early Miocene “Fars Salt” formation (dotted area); emergent Hormuz salt diapirs (red); buried Hormuz salt diapirs (black circle); major faults and structural lineaments (red continuous line, surface expression; dashed line, buried structures); Well location and geological cross sections of Figure 8 (blue lines). Boxes refer to the location of Figures 9–12.

1996; Hessami et al., 2001; Bahroudi and Koyi, 2003; Hudec and Jackson, 2007; Player, unpublished report, 1969) or Jurassic reactivation of basement blocks along the margin of Gondwana [Talbot and Alavi, 1996]. Diapirs sandbox models using X-ray tomography suggested even that the initiation of fold, thrust, wrench fault, and emergent diapirs is also influenced by preexisting salt domes [Letouzey and Sherkati, 2004; Callot et al., 2007].

[8] Previous authors have shown that most of the diapir were already formed at the beginning of the Zagros orogeny [Harrison, 1930, 1931; Kent, 1958, 1970, 1979, 1987; Motiei, 1995; Talbot and Alavi, 1996; Jahani et al., 2007; Player, unpublished report, 1969]. The present paper aims to describe the structure and evolution of the eastern termination of the Zagros Fold-and-Thrust Belt and the effect of preexisting salt diapirs and ridges in the localization and

development of subsequent compressive structures. We have constructed four balanced cross sections based on field and subsurface data, from the Persian Gulf, which constitutes the undisturbed and thus preserved foreland basin, to the inner part of ZFTB, crossing some major diapirs and domes strongly involved in the deformation (Figures 1 and 2). These sections form the basis of a more general discussion on the role of salt diapirs in the structural development of southeastern Zagros.

## 2. Geological Setting and Tectonostratigraphic Context

[9] The study area is bounded by the Main Zagros Thrust (MZT) to the north, the Persian Gulf (representing its

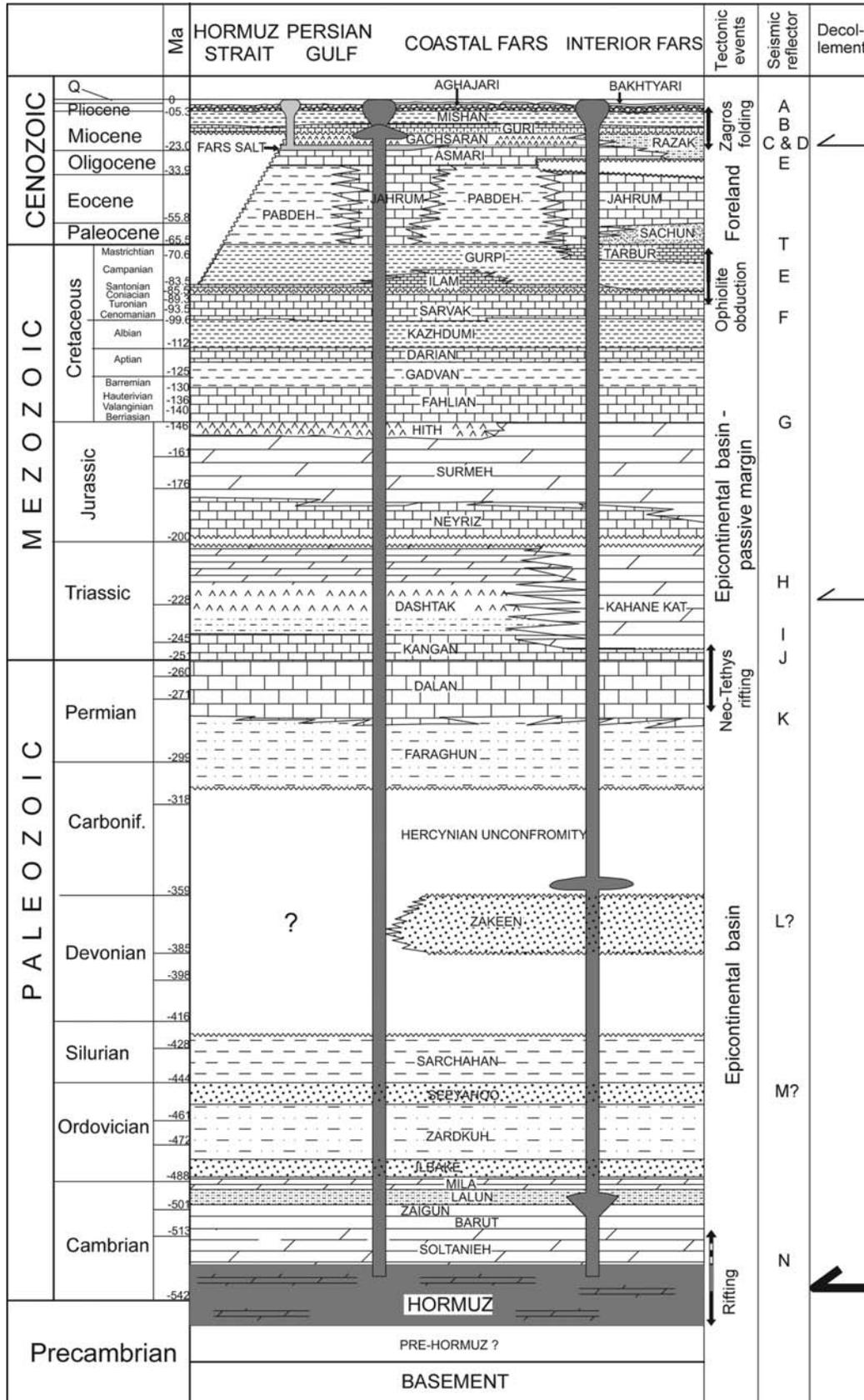


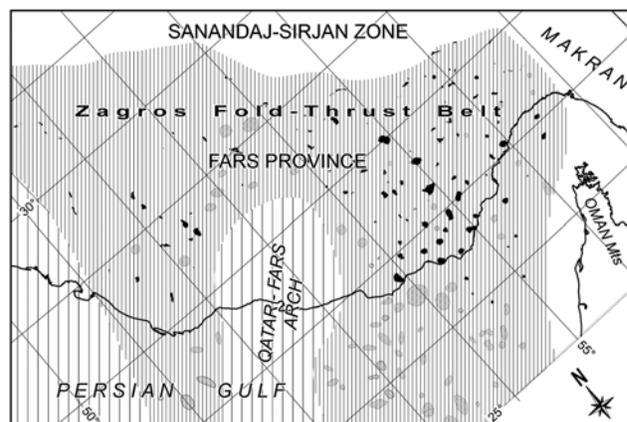
Figure 3

present-day foreland basin) to the south, the Minab Fault to the east and the Oman mountains to the southeast (Figure 1). This region presents a particular complexity due to the overprint of two different orogenic systems, namely, (1) the Late Cretaceous obduction and thrusting that affected the northern border of the Arabian plate from Oman to Cyprus [Ricou, 1971] and (2) the Neogene Zagros-Makran Orogeny [Stocklin, 1968; Falcon, 1969; Ricou et al., 1977; Alavi, 1994].

[10] The oldest portions of the Arabian plate formed in the late Proterozoic (640–620 Ma) when a series of island arcs and microcontinental fragments accreted against the northeastern margin of the African craton [Beydoun, 1991]. These collisional events resulted in a series of N–S structures and were followed, during the Late Proterozoic–Early Cambrian, by a period of rifting that produced subbasins also trending N–S, which controlled the distribution of Hormuz salt in the northern part of the Arabian plate [Beydoun, 1993; Khattab, 1995; Edgell, 1996; Sharland et al., 2001; Amthor et al., 2003; Stampfli and Borel, 2004], and the equivalent Ara salt in Oman [Al Siyabi, 2005; Schoenherr et al., 2007].

[11] The precise stratigraphic sequence of the Zagros has been first established by James and Wynd [1965] and then revised by Setudehnia [1978], Koop and Stoneley [1982], Motiei [1995], and Alavi [2004] (Figure 3). Hormuz salt and equivalent series were deposited in the evaporitic basin mentioned above (Figure 4). This salt layer forms the major décollement level of the area and decouples 10 to 15 km of the overlying sedimentary pile from the pre-Hormuz sediments of unknown age, which rest directly on the basement (Figure 3). Intracratonic continental basins were developed during Early Cambrian–Late Devonian. A postglacial sea level raise in the Silurian led to the deposition of shales. After that, a large sedimentary gap (or erosion) covers the period until the Late Devonian. It was followed by widespread erosion interpreted as the far effect of the Hercynian orogeny. Upper Carboniferous–Lower Permian conglomerates and coarse sandstones deposited unconformably on the underlying truncated beds (Figure 3). They are followed by a carbonate epicontinental platform.

[12] The Neo-Tethys crustal rifting took place during the Late Permian–Early Triassic on the northern flank of Gondwana, north of the ZFTB [Stocklin, 1968; Ricou, 1974; Stampfli and Borel, 2004]. The tectonic setting in Zagros and Oman region changed to a passive margin setting during the Triassic [Ricou, 1974; Falcon, 1974;



**Figure 4.** Map showing the Late Precambrian–Early Cambrian Hormuz salt and evaporitic basin, modified from Kent [1958], Stocklin [1968], Player (unpublished report, 1969), Edgell [1996], H. Motiei (KEPS Company, Simplified table of rock unit in south west Iran, unpublished map, 2001), Bahroudi and Koyi [2003], and Sepehr and Cosgrove [2005]. Dark surfaces denote emergent Hormuz salt diapirs; light gray surfaces denote buried Hormuz salt diapirs. High-density vertical lines denote the extent of the thick salt layer, attested by the presence of emergent diapirs. Low-density vertical lines show the extent of thin Hormuz salt layer.

Stocklin, 1968, 1974; Takin, 1972; Koop and Stoneley, 1982; Setudehnia, 1978; Stampfli and Borel, 2004], which is characterized by marine carbonate sedimentation toward the margin (i.e., to northeast) and evaporite sediments toward the continent [Koop and Stoneley, 1982; Setudehnia, 1978; Motiei, 1995].

[13] During the Jurassic, the southeast Zagros basin is characterized by shallow marine, mostly carbonate successions [Setudehnia, 1978]. Throughout the gulf region, these are partly overlain by an evaporitic sequence passing to carbonate eastward; peloidal-oolitic limestone, shale and marly limestone characterize the Early Cretaceous [Setudehnia, 1978]. Albian shale in the Fars and Khuzestan marks a major marine transgression, which is followed in Cenomanian and Turonian time by carbonate horizons (Sarvak-Ilam formations) [James and Wynd, 1965, Koop and Stoneley, 1982, Motiei, 1993, 1995].

[14] Ophiolite obduction occurred on the northern Arabian plate margin during the Coniacian-Santonian

**Figure 3.** Simplified lithostratigraphic chart of the eastern Zagros Fold-and-Thrust Belt and southeastern Persian Gulf, with the main tectonic events, the major décollement levels, and the stratigraphic position of seismic horizons: seismic reflector A, middle Miocene, top Guri; seismic reflector B, middle Miocene, top Gachsaran/middle Miocene unconformity; seismic reflector C, early Miocene, top Asmari; seismic reflector D, early Miocene, top Fars Salt; seismic reflector E, Eocene, top Pabdeh; seismic reflector T, Mastrichtian, top Tarbur and Gurpi; seismic reflector E, Santonian, top Ilam; seismic reflector F, Albian, top Kazhdumi; seismic reflector G, late Jurassic, top Hith; seismic reflector H, late Triassic, top Dashtak; seismic reflector I, early Triassic, top Kangan; seismic reflector J, late Permian, top Dallan/Khuff; seismic reflector K, early Permian, top Faraghun; seismic reflector L; seismic reflector M, intra-Paleozoic; seismic reflector N, near top Hormuz Salt. Dark gray column indicates Hormuz salt diapir, and light gray column presents Fars salt diapir. The data are extracted from previous published data [James and Wynd, 1965; Motiei, 1995], unpublished data from NIOC, and subsurface data (this study).

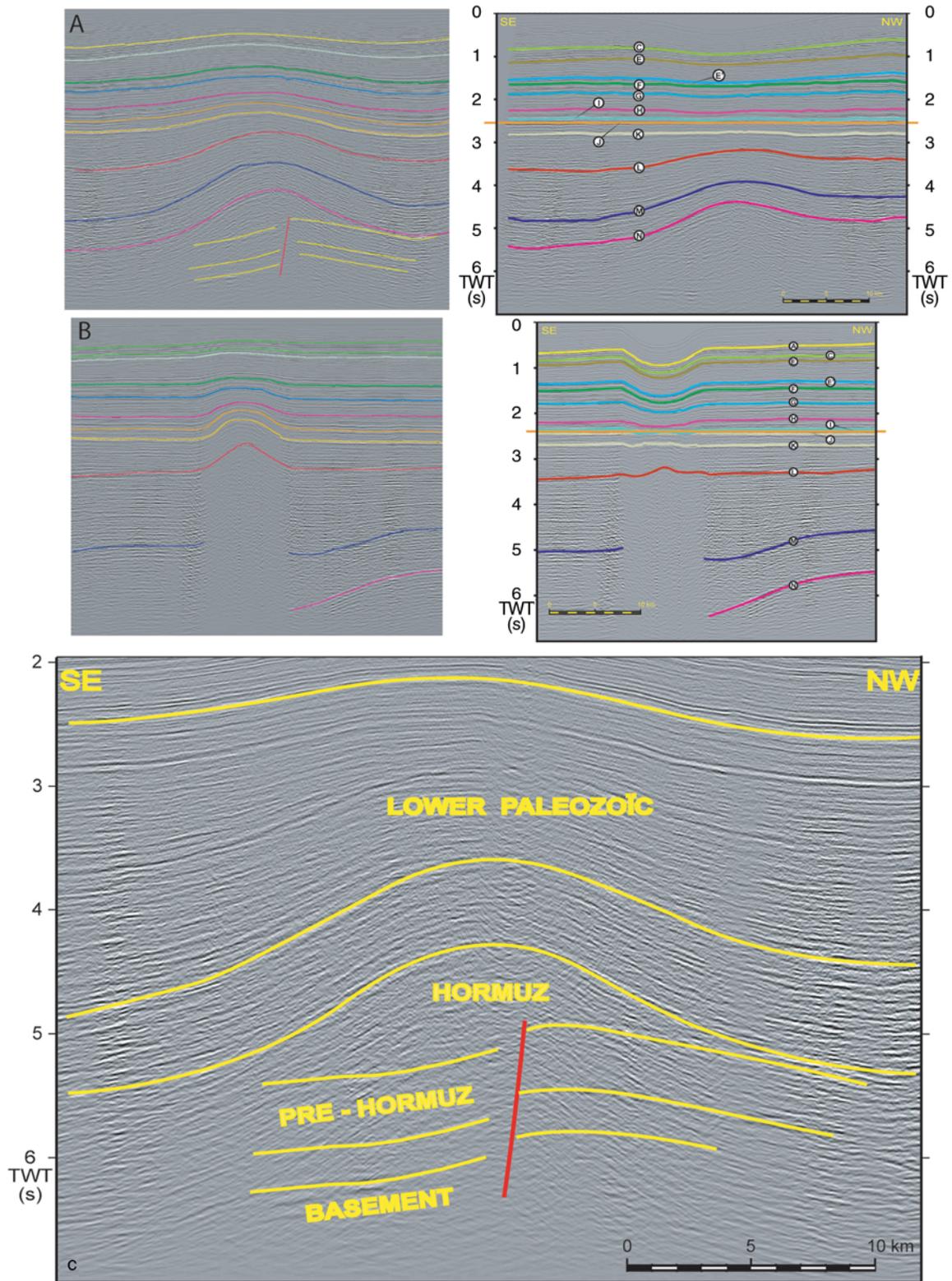
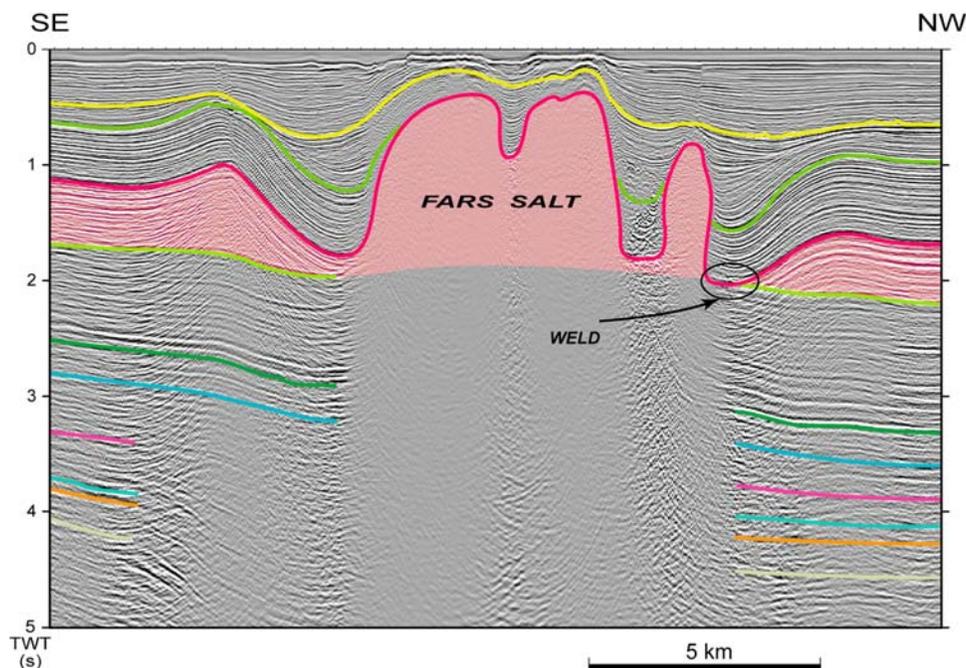


Figure 5



**Figure 6.** Seismic image showing shallow diapirism, rim synclines, and salt weld, affecting the early Miocene Fars Salt layer. Because of shallow diapirs and rapid lateral velocity variations, processing was not able to image the underlying structures. Some of the Fars salt structures are clearly located over undeformed horizons, But others could be superimposed over deep Hormuz diapirs, active during the Fars salt deposition. Thickness variations adjacent to the Fars salt structures show that salt movement started just after few overburden. For age of the reflectors, see Figure 3.

[Ricou, 1971; Ricou et al., 1977; Berberian and King, 1981; Agard et al., 2005]. This pattern is well preserved in the Oman Mountains, where a slice of oceanic crust, slope sediments, and underlying thrust sheets made of carbonate rocks can be observed [Warrak, 1996; e.g., Searle et al., 2004]. A regional uplift following the ophiolite obduction caused local erosion of the Cenomanian-Turonian carbonates [Setudehnia, 1973; Stoneley, 1981; Motiei, 1993].

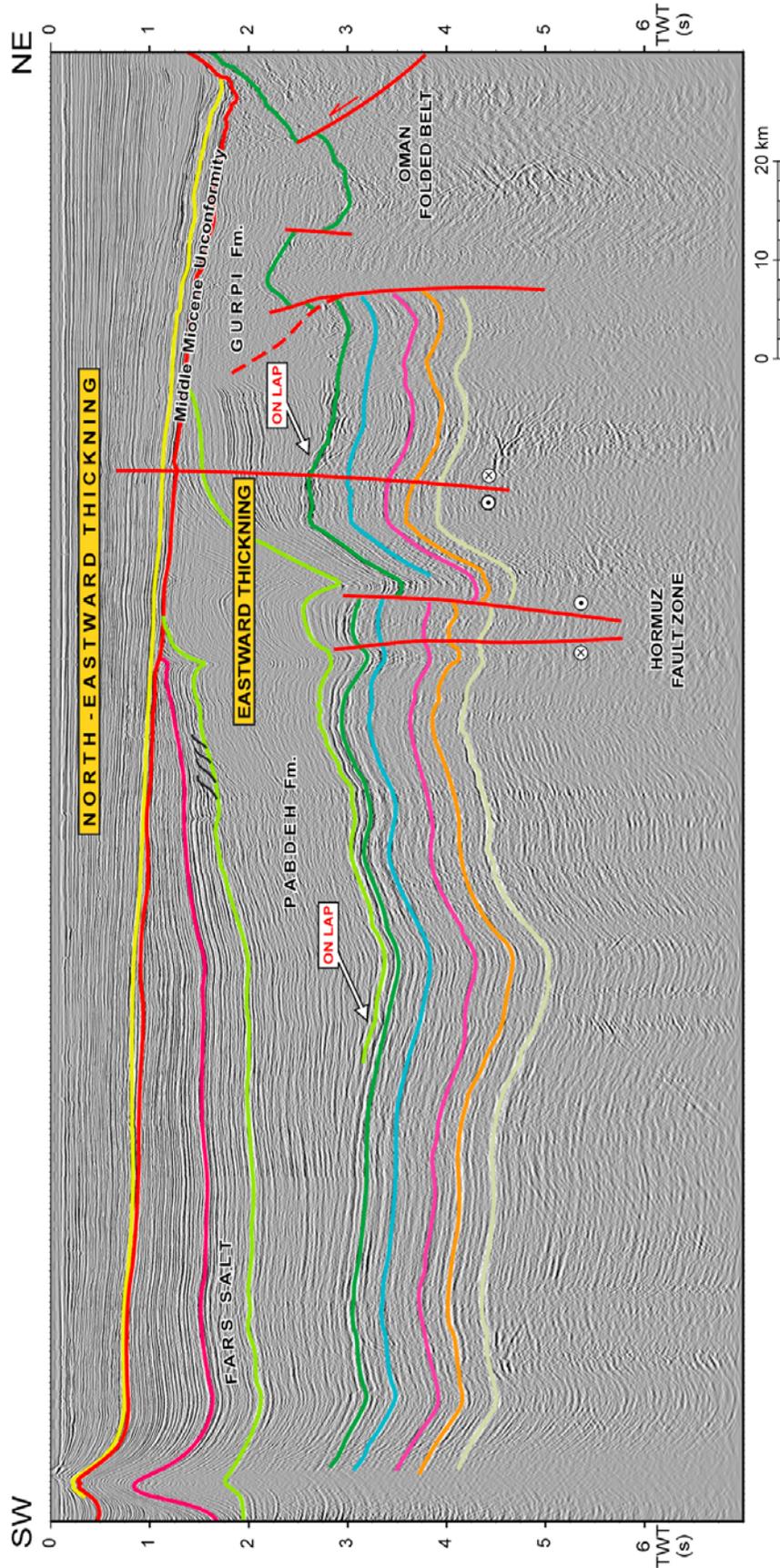
[15] Continuous subduction of Neo-Tethys led to the development of an over-deepening fore-arc basin. During the Campanian-Maastrichtian, deep water marls, shales and marly limestone extended uniformly over most of the Zagros. In the interior Fars and Bandar-Abbas hinterland, Maastrichtian marls laterally changed to reefal limestone [Koop and Stoneley, 1982; Warburton et al., 1990; Motiei, 1993; Sharland et al., 2001]. Accommodation space has

been created, and deep-water shales were deposited during the Paleocene-Eocene, but in the interior Fars, carbonate rocks were deposited on a ridge, which likely corresponds to a fore bulge in front of the subducting Neo-Tethys.

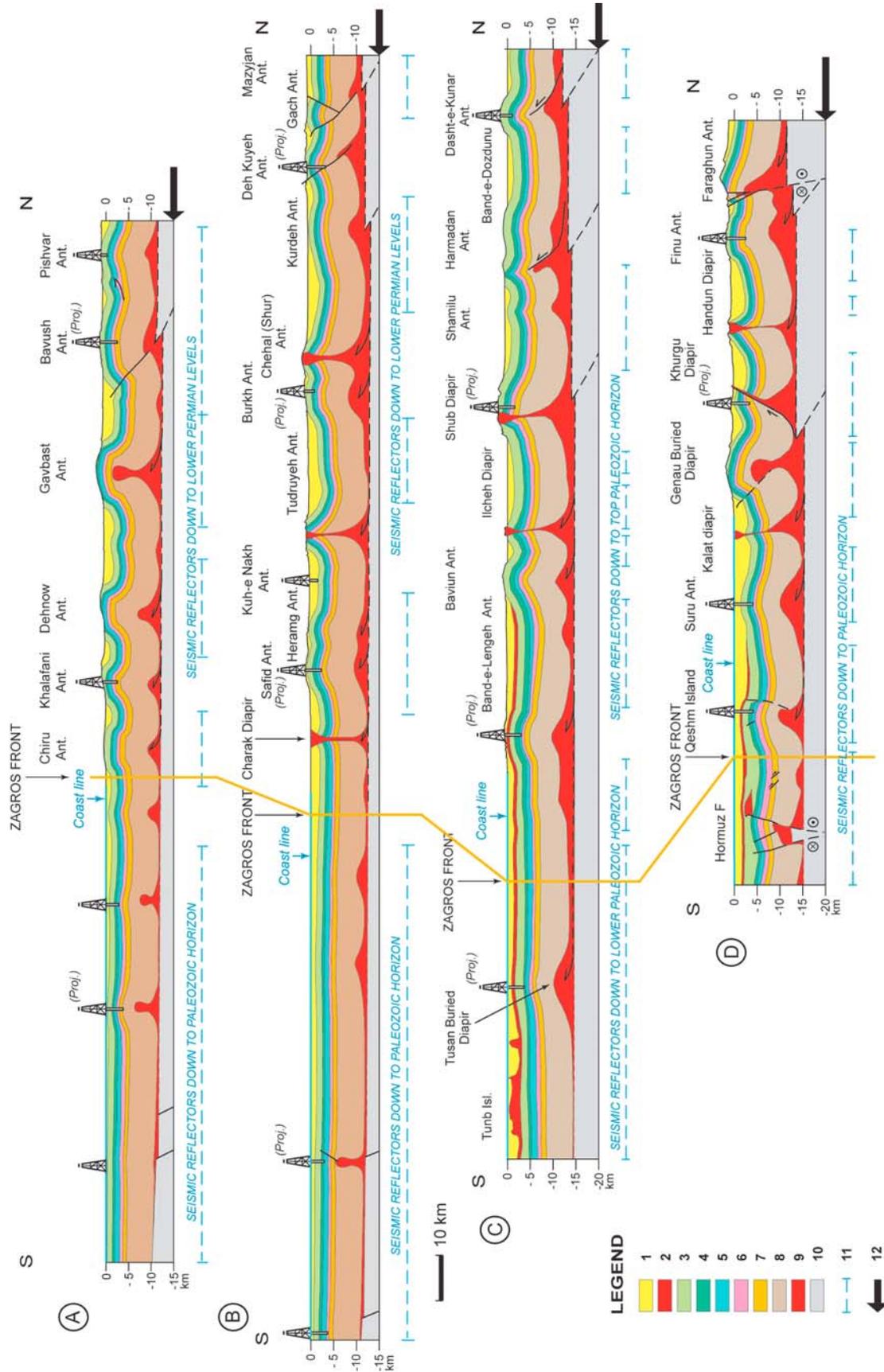
[16] During the late Oligocene–early Miocene, the Zagros and Persian Gulf received the shallow marine Asmari limestone. A local evaporitic facies, called the Fars salt, was deposited during the lower Miocene to the west of the Hormuz strait (Figure 2). This Fars salt is a lateral equivalent of the upper Asmari limestone. It was formed from recycled Hormuz salt derived from outcropping diapirs in a restricted basin related to the closure of the Hormuz Strait as a consequence of the Miocene uplift of the Oman Mountains.

[17] The Neo-Tethys ocean was closed by the late Oligocene–Miocene continent-continent collision and the

**Figure 5.** Interpreted seismic images describing lived up-doming and thinning above the buried salt diapir due to salt activity from Early Paleozoic to recent. Sections A and B were flattened at the top of the Paleozoic to produce Figures 5a (right) and 5b (right) (flattening at the J horizon, top Dalan/Khuff formations). (a) An initiation time for salt activity at nearly (M) reflector's age (Early Paleozoic) and a maximum activity during Paleozoic with thickening between the M and K horizons. (b) In contrast, a quasi-continuous activity during Paleozoic and Cenozoic, with a cessation of activity during the Late Paleozoic. (c) A close-up from Figure 5a showing the top of the Hormuz salt and an underlying normal fault probably associated to the initiation of the salt pillow in Early Paleozoic. Note the presence of pre-Hormuz strata, already described in the northern Fars province [Letouzey and Sherkati, 2004]. Such pre-Hormuz strata also exist in the coeval Ara Salt basin in Oman (Abu Nahara and Nafun formations [Peters et al., 2003; Loosveld et al., 1996]). For age of the reflectors, see Figure 3.



**Figure 7.** Seismic image showing the middle Miocene unconformity under the Guri member in the Hormuz Strait area. Compressive structures and truncations below this unconformity show that the Oman Mountains were uplifted by compression and were eroded before the mid-Miocene. Notice the uplift and erosion of the Cretaceous carbonate platform in the east of the section, as well as the horst or “push-up” structure (Hormuz fault zone), sealed by the unconformity. Notice also the progressive (tilted) onlaps to the west of the late Cretaceous–Paleogene Gurpi and Pabdeh pelagic marls above the Ilam-Sarvak platform carbonates. Deposition of the Guri carbonates and Mishan marls above the unconformity mark the opening of the Hormuz Strait with the Zagros-Makran flexure to the northeast. For extension of the mid-Miocene unconformity and age of the reflectors, see Figures 2 and 3, respectively.



whole Zagros belt was uplifted at the end of Pliocene time [Stocklin, 1968; Alavi, 1994; Berberian, 1995; Vergés *et al.*, 2003; Sherkati and Letouzey, 2004], likely as a consequence of slab break-off [Molinari *et al.*, 2005a]. Growth strata in the late Miocene–Pliocene are attributed to the main phase of folding [Homke *et al.*, 2004; Sherkati *et al.*, 2005; Mouthereau *et al.*, 2007b]. Finally, Plio-Pleistocene conglomerates were deposited unconformably after the main phase of folding but is often affected by recent to ongoing deformation.

[18] Southwestward cumulative shortening through the Zagros Fold-and-Thrust belt give values of 33 km to 49 km in the Dezful Embayment and Izeh Zone [Blanc *et al.*, 2003; Sherkati *et al.*, 2006], and 25 km to 69 km in the Fars Arc [McQuarrie, 2004; Sherkati and Letouzey, 2004; Molinari *et al.*, 2005b; Sherkati *et al.*, 2006; Mouthereau *et al.*, 2007a]. In the basement, shortening is accommodated, at least partly, by distributed thrusts as suggested by fault plane solutions [Talebian and Jackson, 2004; Tatar *et al.*, 2004]. But how the lithosphere accommodates shortening at greater depths remains unknown [Paul *et al.*, 2006].

### 3. Southeastern Persian Gulf as a Model of Prefolding Configuration of the Eastern Zagros

[19] The nearly landlocked Persian Gulf (Figure 1) represents the current foreland basin of the Zagros Mountains. The present geometry of salt structures in the Persian Gulf is not affected by Zagros folding yet (Figure 2), and could be considered as an image of the prefolding configuration of eastern Zagros.

#### 3.1. Hormuz Salt Basin

[20] The Hormuz salt basin is pinched out westward, against the normal paleofaults bounding the Qatar Arch and the stable Arabian plate, but extends northward onshore in the southeastern Fars province (Figure 4). In the eastern Zagros, although if it is not the dominant opinion, the independence between folding and initiation of salt movement has been put forward by Harrison [1930], Kent [1958, 1970], Player (unpublished report, 1969), and Jahani *et al.* [2007] on the basis of field observation, namely reworked Hormuz material and progressive unconformities (i.e., growth strata) in the vicinity of salt diapirs. For these

authors, salt movement occurred in Southern Fars since the Late Cretaceous for many diapirs and even since the Late Permian for some of them [Motiei, 1995].

[21] About 217 Hormuz salt plugs and domes are referenced in the ZFTB and Persian Gulf (buried salt diapir in nearby Arabian countries excluded) [Harrison, 1931; Gansser, 1992; Kent, 1958, 1979; Trusheim, 1960; Huber, 1975; Kent and Hedberg, 1976; Edgell, 1996; Jahani *et al.*, 2007; Player, unpublished report, 1969]; 132 breached to the surface forming plugs or island, whereas the others (85) are buried salt diapirs mostly known in the southeast of the Persian Gulf (Figure 4).

#### 3.2. Halokinesis

[22] On seismic lines, the salt domes show an increase of layer thickness from top of dome to rim syncline (Figures 5a and 5b). Such a feature is interpreted as evidence for a progressive draping of the deep horizons (N, L, M in the Lower to Middle Paleozoic) and down building of the lateral minibasins [Jackson and Talbot, 1991; Vendeville and Jackson, 1992; Schultz-Ela, 2003; Rowan *et al.*, 2003a, 2003b; Jahani *et al.*, 2007]. Using these data, we infer that up doming and growth of most of the domes started in the early Paleozoic and continued up to the Present (Figures 5a and 5b). It is worth noting that few salt diapirs observed in seismic images in the Persian Gulf originated from the shallow Fars salt level (Figures 2 and 6).

#### 3.3. Mid-Miocene Unconformity

[23] Another structural feature of the southeastern Persian Gulf is the unconformity below the middle Miocene limestone (Figures 2 and 7). This unconformity seals compressive, and wrench faulting related (push-up) structures as well as their subsequent erosion (Figure 7). These structures are related to the Oligocene–early Miocene Oman Mountains uplift (UAE Ministry of Energy, The geology and geophysics of the United Arab Emirates, report on advanced seismic interpretation, 4 volumes, unpublished reports, 2007), which is coeval with the onset of collision in the Zagros. On the seismic line (Figure 7) one can observe two sedimentary wedges, corresponding to two periods of flexuring, separated by the unconformity. The slope of the first flexure was eastward as shown by the progressive onlap to the west of the late Cretaceous and Paleogene above the Mid-Cretaceous platform carbonates (onlaps are

**Figure 8.** Regional geological (a) cross section A, (b) cross section B, (c) cross section C, and (d) cross section D from the Persian Gulf to inner parts of the ZFTB (see Figure 2 for location). Zigzag line to the left indicates the Zagros front, so salt structures to the south are only salt domes or diapirs, whereas in the folded zone it could be either diapirs or pillow in the core of detachment fold. Dashed blue lines under each cross section indicate the position of the seismic lines used to draw the cross sections. The black harrow on the left of the sections, show the shortening deduce from horizon length. In the absence of good seismic image at depth, pre-Hormuz sediments which exist in the area are not represented. For the same reason we artificially draw a “flat basement” (see the text), ignoring the faults from the early Paleozoic rifting event (see examples on Figure 5). Salt diapirs as well as the thickness variations around them are inferred from seismic images and surface data. However, seismic images do not allow precise definition of the depth and shape of buried diapirs and domes: 1, Neogene; 2, lower Miocene Fars Salt; 3, Upper Cretaceous and Paleogene; 4, Lower to Middle Cretaceous; 5, Jurassic; 6, Triassic; 7, Upper Paleozoic; 8, Lower Paleozoic; 9, Hormuz Salt; 10, pre-Hormuz sediments and basement; 11, seismic line; 12, shortening.

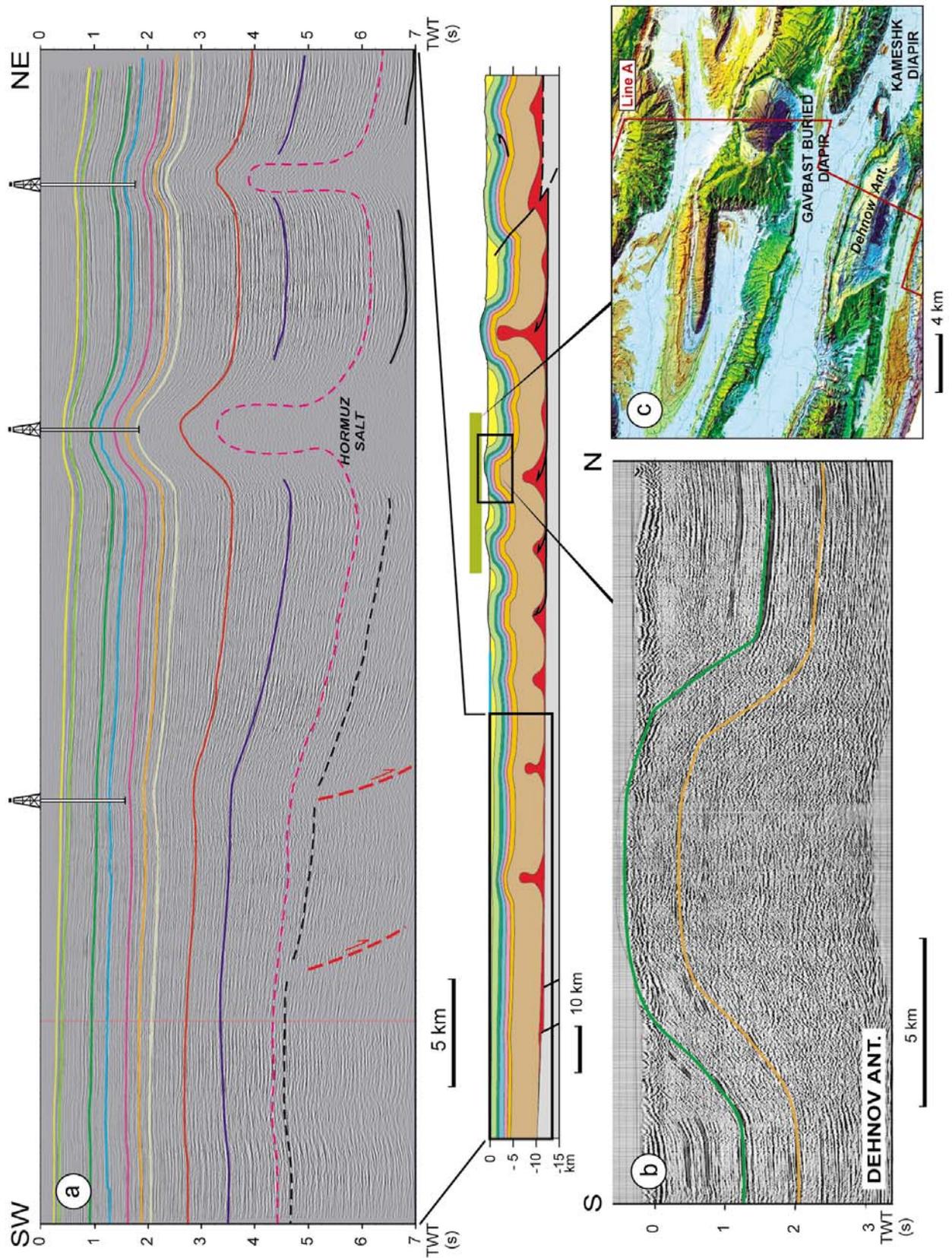


Figure 9

tilted during later uplift and compression) (Figure 7). This basin, locally oriented N–S, is the northern prolongation of the Late Cretaceous–Paleogene foredeep developed in front of the Oman Mountain during and after the ophiolite obduction [Boote *et al.*, 1990]. The second flexure, younger than the mid-Miocene unconformity, shows tilting toward the N–NE. It corresponds to the foredeep of the Zagros during continental collision and mountain building. Opening of the Hormuz strait, by submerging of the north trending Oman Mountains at that time, allowed connection between the Indian Ocean and the Zagros foredeep. Confined evaporitic and salt facies of the Fars salt and Gachsaran formations change to open marine facies (Guri limestone and Mishan marls).

## 4. Geometry and Kinematics of Folding

### 4.1. Data Set and Methodology

[24] Four geological cross sections (Figures 2 and 8) were drawn from (1) seismic images, which cover the most part of the sections (blue line under each section), (2) unpublished geological maps from NIOC, (3) well information, and (4) field data. The sections were selected in order to cross the main structures and salt domes. The main criterions were the existence of seismic images and the proximity of wells. Only a few wells reached the top of the Devonian and Silurian. Two horizons, the Albian shale and Upper Permian limestone are key reflectors followed regionally both offshore and onshore. The oldest interpreted horizon offshore corresponds to the top of the Hormuz salt, which is in general quite difficult to follow everywhere. Due to its depth and possibly to the low velocity contrast with the overlying rocks it is difficult to image. However, offshore, out of the folded zone, it is locally possible to image the salt, and even some presalt horizons cut by normal faults (Figure 5a). These normal faults seem to control the Hormuz salt deposition toward the Qatar Arch, and the presalt normal faults seems to be inherited from a Late Proterozoic rifting event. Due to the absence of deep horizons in most of the studied area, we did not draw these presalt structures, but they likely exist in most of the onshore domain.

[25] The cross sections have been drawn first in time then converted in depth. Time-depth conversion from above early Paleozoic has been done based on 35 check shots from well data offshore and onshore. We used classical time depth conversion based on velocity maps from different stratigraphic intervals. An estimated average velocity of 4500 ms (reasonable at that depth for both clastic and salt rocks) was used for the time depth conversion of the Lower Paleozoic horizons. Thickness of the Lower Paleozoic offshore is about 6 km and seems to reach locally 8 km in the deepest part of the basin. To built the sections, we

postulate a 6 km thick lower Paleozoic both onshore and offshore. Adding 5 to 8 km of younger sediments, the total thickness of the sedimentary pile above the Hormuz salt layer ranges between 11 and 15 km.

[26] The kink method was used to build the cross sections in the folded zone [Suppe, 1983]. The dips measured on the competent layer during the field surveys were projected at depth. Each panel of constant dip is separated by narrow hinge lines from the next one. We used *Dahlstrom's* [1969] method for the shortening estimation of each cross section (Figure 8).

[27] At large scale, we observe a regional northeastward flexure. The low taper observed in this region of the Zagros is compatible with the low basal friction at the base of the folded belt, due to the thick basal salt detachment level and to the low flexural deep deduced from tomography in the northern Fars region [Paul *et al.*, 2006; Nilforoushan, 2007]. The offshore geometry is more complex with an additional eastward regional dip related to the Oman paleoflexure system (Figure 8d). Vertical displacements along blind basement faults in the northern part of the sections were inferred by calculating the amount of uplift at the bottom of adjacent synclines on the same Mesozoic or Cenozoic seismic horizons and inferring a constant thickness for the lower Paleozoic. Thickness variations and erosion of Neogene sediments associate with these faults, as well as fault plane solution in that region [Talebian and Jackson, 2004] strongly suggest reverse component along such a fault.

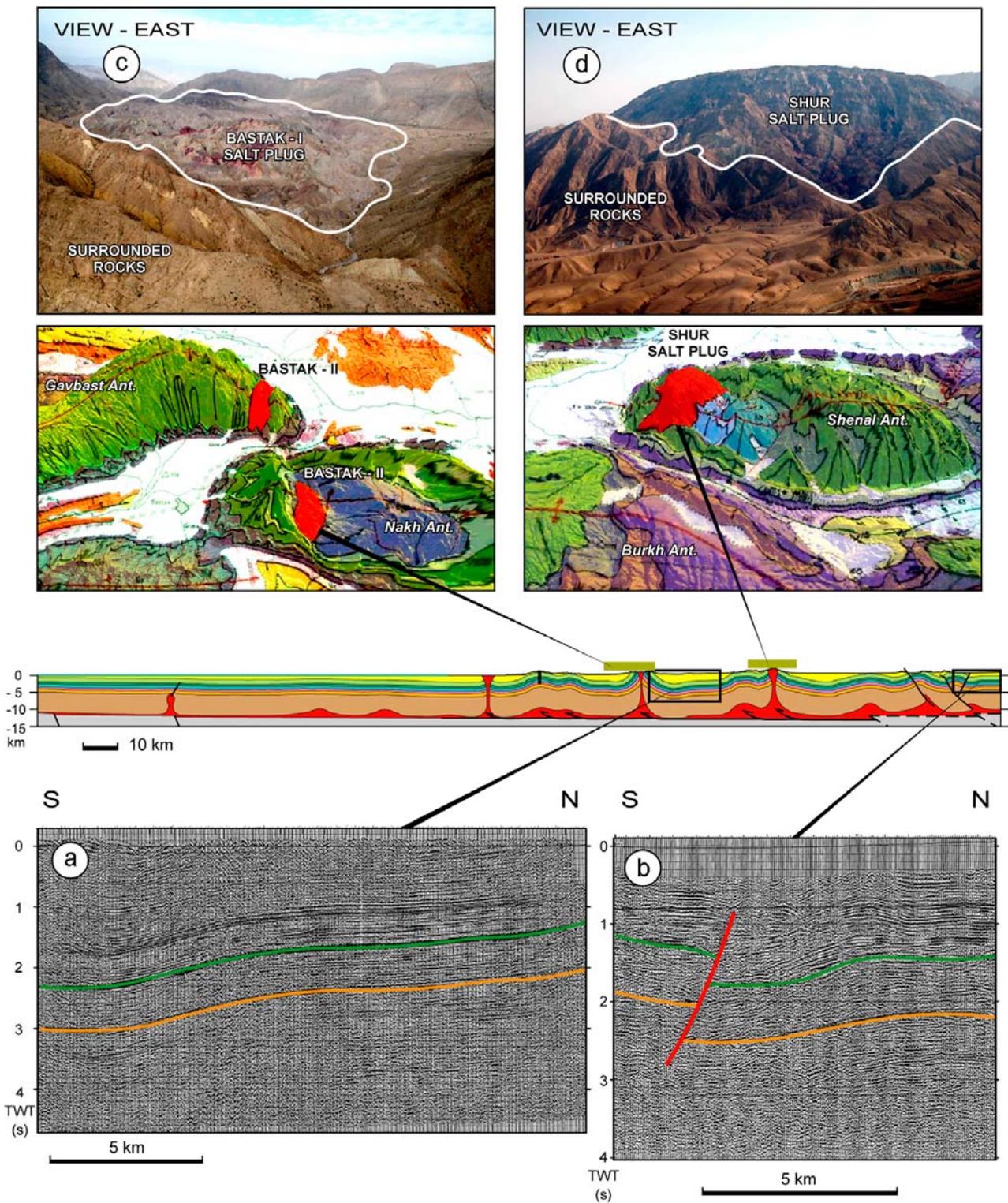
[28] In all the cross sections (Figure 8), the tectonic style is dominated by detachment folding above the Hormuz salt. Only few local and minor intermediate detachment levels have been observed in Triassic (Dashtak evaporites) and late Neogene levels (Gachsaran salt) (Figures 3, 8a, 8b, and 8c).

### 4.2. Presentation of the Cross Sections

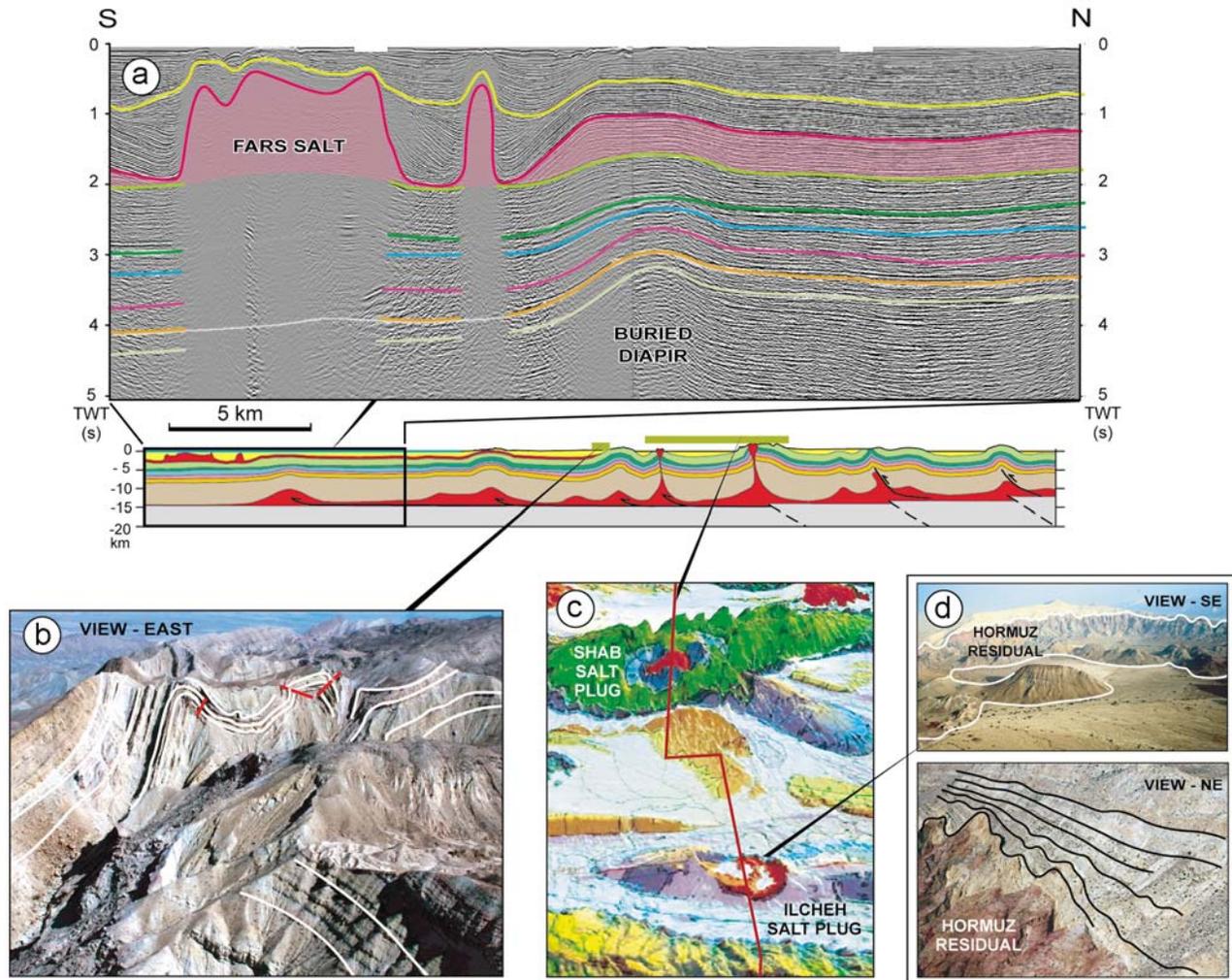
#### 4.2.1. Cross Section A

[29] The length of cross section “A” is 230 km with 105 km in the Persian Gulf foredeep, and 126 km in the ZFTB (Figure 8a). The measured shortening from the deformation front to the northern tip of the section is 12.7 km (9%). Offshore sections show the location of the main basement faults that accommodate flexuring of the margin on the eastern margin of the Qatar Arch (Figures 2 and 9a) and the general northeastward thickening of the sedimentary pile (Figure 9a). The three salt domes are buried along the offshore section (Figures 8a and 9a) and were active before Zagros folding. Gavbast circular dome is located at the junction of three anticlines (Figure 9c). This dome was also active before Zagros folding [Jahani *et al.*, 2007]. Four box anticlines, interpreted as salt-cored detachment folds are crossed by this section (Figures 9b and 9c). The Dehnow Anticline (Figure 9b) [Jahani *et al.*, 2005] is

**Figure 9.** Seismic and image along section “A” (Figures 2 and 8). (a) Offshore section showing the main interpreted horizons, the basement flexure accommodated by the northeastward thickening of the sedimentary pile, and two buried Hormuz diapirs. (b) Seismic image of the salt-cored Dehnow box fold. (c) Geologic map of the two box folds Dehnow and Gavbast, which are cored by a buried Hormuz salt diapir. For age of the reflectors, see Figure 3.



**Figure 10.** Seismic and image along section “B” (Figures 2 and 8). (a) Seismic image showing a rim syncline northward of the Bastak “1” diapir interpreted as down building due to lateral salt migration at depth. (b) Seismic image showing a back thrust north of the Gach Anticline. For age of the reflectors, see Figure 3. (c and d) Digital elevation model together with helicopter pictures of the Bastak “1” salt diapir and Shur active salt diapir, respectively.



**Figure 11.** Seismic and image along section “C” (Figures 2 and 8). (a) Seismic image showing a large zone filled by Fars salt (red color). Hormuz salt diapir forms a buried structure in the center of the image. For age of the reflectors, see Figure 3. (b) Photographs illustrate collapse and rabbit structure along the south limb of the Baviyun anticline, due to shallow detachment along Fars salt and Gachsaran evaporitic levels. (c) Digital elevation models. (d) Aerial pictures showing the Ilcheh inactive diapirs. Notice the remnants of Hormuz insoluble blocks, which were formerly brought up by the salt and local growth strata in the Miocene rocks around the diapir.

combines two smaller “en échelon” anticlines. The wide ones detached on Hormuz basal décollement layer, whereas the long-narrow anticline developed on the Middle Triassic intermediate detachment level. A recent basement thrust fault is inferred below the Bavush anticline due to the different elevation of seismic horizons between adjacent synclines.

#### 4.2.2. Cross Section B

[30] Cross section “B” is 283 km long, divided in 113 km offshore and 170 km in the ZFTB (Figure 8b). It exhibits two recent basement thrust faults, deduced from different elevation of seismic horizons in adjacent synclines, and a back thrust visible on seismic image (Figure 10b). The measured minimum shortening is 10.5 km (6%) over the whole section. Despite the longer length of section B through the folded belt (44 km), shortening is 2.2 km

shorter than in section A. This could be interpreted as a consequence of the presence of two squeezed diapirs, each of them being 3 km in width originally [e.g., Callot *et al.*, 2007; Rowan and Vendeville, 2006].

[31] Transect “B” crosses three salt domes in the Persian Gulf, and three salt diapirs in the ZFTB (Figures 10c and 10d). All of them were active before Zagros folding [Harrison, 1931; Kent, 1958, 1970, 1979; Jahani *et al.*, 2007; Player, unpublished report, 1969]. The Charak diapir, located at the periclinal termination of the Charak anticline, is a mature diapir characterized by a crater filled to the rim by salt with irregular surface [Jahani *et al.*, 2007]. The walls of the crater are made of steep to overturned late Neogene beds with local growth strata. The Bastak and Shur diapirs show active salt extrusion. Bastak 1 is located in the western nose of the Nakh anticline and encompassed by

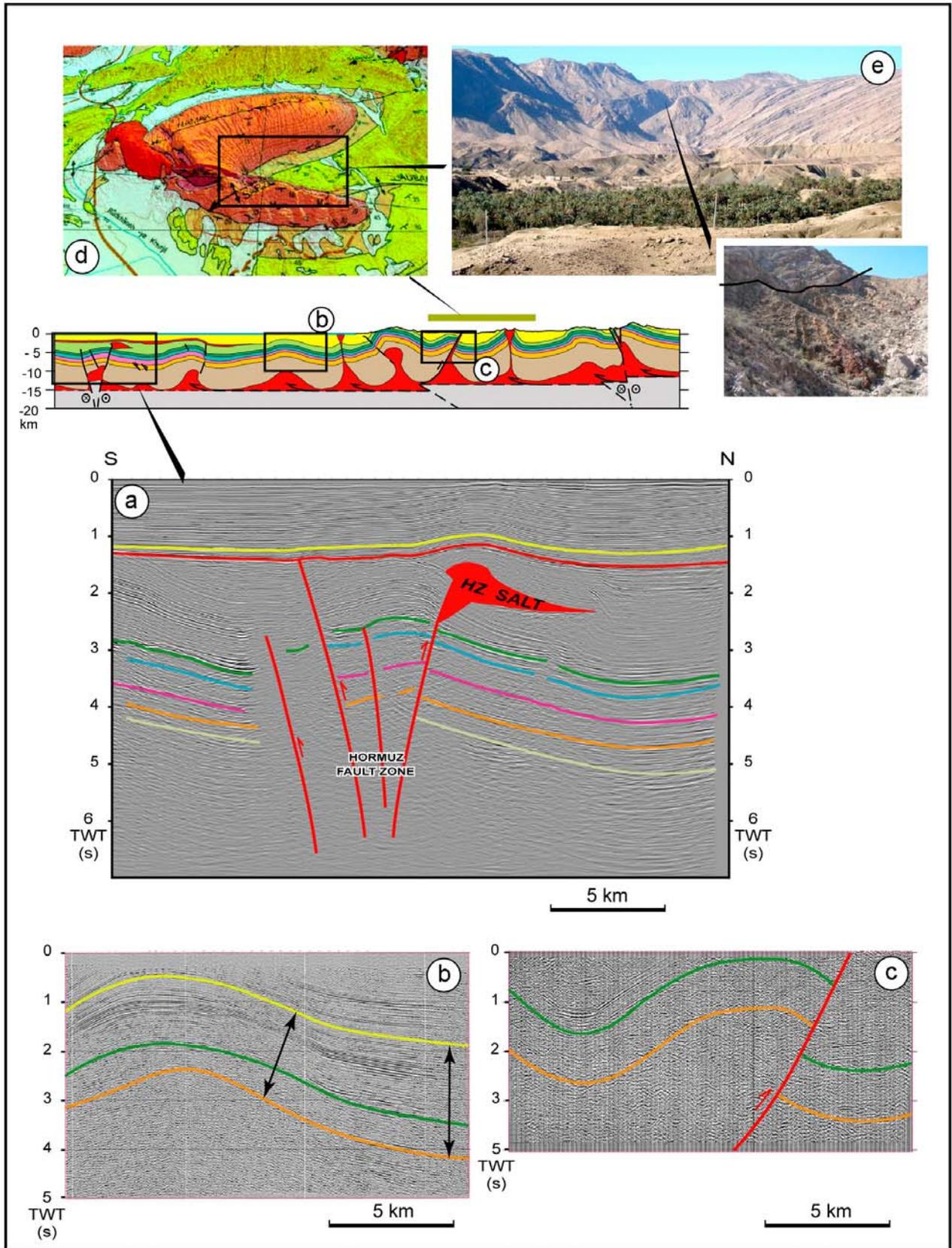


Figure 12

huge cliffs (Figure 10c). Surrounding strata of Upper Triassic to Quaternary age show neither recycled Hormuz debris nor growth strata, but paleontologic data show that most of Upper Jurassic to Lower Cretaceous rock units is lacking (Player, unpublished report, 1969). This suggests that Bastak 1 was a buried dome before Zagros folding. Shur (also called Chehal) diapir is located at the eastern termination of the Shur anticline. It stands nearly 2000 m above sea level and is one of the highest diapirs in the Fars Province (Figure 10d). It is confined within Middle Cretaceous to lower Miocene rocks [Jahani et al., 2007].

[32] Six salt cored detachment anticlines are crossed by transect B, the two more internal being cut out by thrust faults. Fold wavelengths vary from 10 km in Herang to 18 km in Kurdeh anticline.

#### 4.2.3. Cross Section C

[33] The length of section “C” is 243 km, 72 km in the Persian Gulf and 171 km in the ZFTB (Figure 8c). The minimum shortening accommodated by folding is 10.3 km (6%). Offshore, the section crosses several salt diapirs and ridges, which originated from the Miocene Fars salt layer (Figure 11a). Due to shallow diapirs and rapid lateral velocity variations, processing was not able to image the underlying structures because the young salt structures obscured the deep structures. Onshore, the section passes through two Hormuz diapirs, Ilcheh and Shab (or Shu) (Figures 11c and 11d). Ilcheh is an inactive empty crater with few remnants of Hormuz insoluble blocks, which were formerly brought up by the salt (Figure 11d). The surrounding rocks contain recycled Hormuz material [Harrison, 1930, 1931; Kent, 1958; Player, unpublished report, 1969] and growth strata of Miocene age [Jahani et al., 2007]. Shab is located at the culmination of the Shab anticline. This active diapir is embedded in Jurassic to Oligocene rocks and presents Late Cretaceous earliest movements as shown by local growth strata [Jahani et al., 2007].

[34] Section “C” also crosses six salt cored detachment anticlines, with large intervening synclines. Average wavelength is 15 km. Early Miocene Fars salt acted as a shallow intermediate detachment level and generated collapse and “rabbit-ear” structures along the south limbs of the Baviyun (Figure 11b) and Bandar-E-Lengeh anticlines. Northward, we postulate the existence of three basement thrust faults at depth, as deduced from the vertical shift of the syncline base levels.

#### 4.2.4. Cross Section D

[35] Cross section “D” (Figures 8d and 12), situated close to the buried Oman structures (Figures 2 and 3), is a little more complex than the other sections. It is 168 km long with 26 km in the foreland and 120 km in the folded

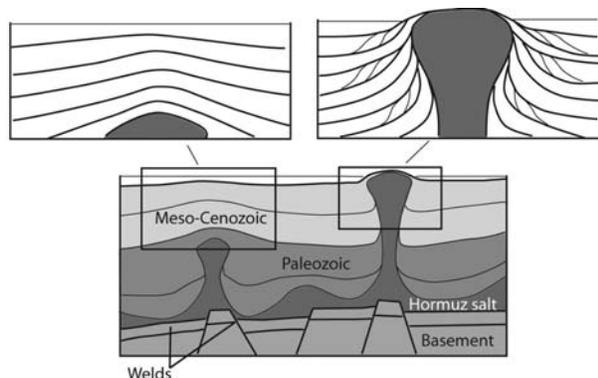
zone. The measured minimum shortening is 11.7 km (7%). At the southern tip of the section seismic lines display the middle Miocene unconformity (Figure 12a).

[36] The section crosses four salt plugs (Kalat, Khurgu, Handun, and Finu) and one buried salt diapir, Genau. Offshore, the section passes nearby the Larak Island, which is an outcropping Hormuz diapir [Kent, 1987]. The seismic section (Figure 12a) crosses the “Hormuz Fault Zone” (Figure 2), interpreted as a positive flower structure. This fault zone is a tear fault active during the Oligocene and early Miocene compression and the related uplift of the Oman Mountains, with emergence of Hormuz salt glacier at that time (Figure 12a). Diapirs cropping out along such tear faults either in pull-apart structures [Talbot and Alavi, 1996; Koyi et al., 2008] or in push up zones correspond to reactivated preexisting diapirs [Letouzey and Sherkati, 2004].

[37] Khurgu is an active diapir located at the junction between the Namak and Siah anticlines (Figures 12c and 12d). Recycled Hormuz debris has been observed in late Oligocene–early Miocene levels [Jahani et al., 2007; M. F. Shepherd, Iranian Offshore Oil Company, Note on the coastal structures of the Bandar-Abbas area, unpublished report 871, 1957]. The inactive Handun salt dome emerged in the core of the Handun anticline and is responsible for its particular “peanut” shape (see, e.g., Callot et al. [2007], compare discussion below). Local growth strata and recycled Hormuz materials show that it formed a dome in the Eocene-Oligocene that emerged during the Miocene.

[38] Seven salt-cored anticlines, East Qheshm, Suru, Ginau, Namak, Handun, Finu, and Faraghun, are crossed by the section (Figure 8d). Two large structures, Genau and Faraghun, are inherited from preexisting salt domes. Contrast in basement elevation on seismic section (more than 1500 m) suggests that the Genau structure is associated with a basement thrust fault. In the case of Faraghun structure Paleozoic rocks cropped out at the vicinity of Miocene age rocks on the surface. The rapid thinning of beds toward the anticline hinges and the huge but apparent stratigraphic overlap are explain if one consider the thinning of beds and stratigraphic section reduction toward the inherited domes. Gahkum, Faraghun, and Khush-Kuh are large en echelon fold located along a NW–SE dextral shear zone, cutting the northeastern corner of the Zagros platform. Namak and Siah twin anticlines are separated by an oblique fault showing a combination of updip and right-lateral components (Figures 12c, 12d, and 12e). A 7.0 magnitude earthquake occurred along this fault in 1977 [Berberian and Papastamatiou, 1978]. Fault plane solutions of earthquakes present nearly pure thrust faulting with focal planes

**Figure 12.** Seismic and image along section “D” (Figures 2 and 8). (a) Offshore section crossing the Hormuz fault zone (Figure 2), capped by the middle Miocene unconformity. The activity of this right-lateral wrench fault system, related to the Oligocene–early Miocene Oman Mountains uplift, triggered the activity of salt extrusion. Allochthonous salt glaciers (“namakier” [Mohr et al., 2007]) illustrated by this section were found along this fault system. Age of the reflectors is given in Figure 3. (b) Thickening of the Paleozoic and Mesozoic section in the syncline between the Suru and Ginau anticlines. This thickening is due to the withdrawal of Hormuz salt around the nearby Kalat diapir. (c) Thrust fault. (d) Thrust fault in between the Siah and Namak anticlines. (e) Thrust fault observed at surface with right-lateral oblique component.



**Figure 13.** Sketches of the two possible initial states of Hormuz diapir in the eastern Zagros, before folding: either (right) emergent or nearly emergent diapirs since Early Paleozoic or (left) buried diapirs or domes since the late Early Paleozoic time with draping of Mesozoic and Cenozoic strata (modified from *Jahani et al.* [2007] with kind permission of Springer Science and Business Media). Schematic cross section is oriented from south to north.

concordant with a south dipping reverse fault [*Molinaro et al.*, 2004](Figure 10b).

## 5. Discussion

### 5.1. History of Salt Diapirism in the Southeastern Fars

#### 5.1.1. Initiation and Growth

[39] In the Persian Gulf as well as in the Eastern ZFTB, several seismic lines show that deposition of the Hormuz salt is controlled by the late Proterozoic–early Paleozoic rifting event. Initiation of movement of Hormuz salt occurred as early as the Lower Paleozoic (Figure 5). Generally salt activity is mostly controlled by tectonic events, sedimentary supply, and overburden thickness, but the primary driving force in the eastern Zagros has not been defined yet. The role of tectonic events, in particular extensional faulting, in triggering the initiation of salt diapirs and ridges is well known [*Jackson and Vendeville*, 1994; *Vendeville et al.*, 1995; *Stewart*, 2007] and is suggested by seismic sections (Figure 5c). The increase of layer thickness from top of dome to the rim syncline in Early Paleozoic suggests that onset of salt movement is due to Early Paleozoic rifting. Postdepositional salt movement triggered by differential loading of thick continental clastics onto the mobile substrate, as suggested for the Ara salt in Oman by *Loosveld et al.* [1996], is an additional or alternative explanation for triggering the early salt movement.

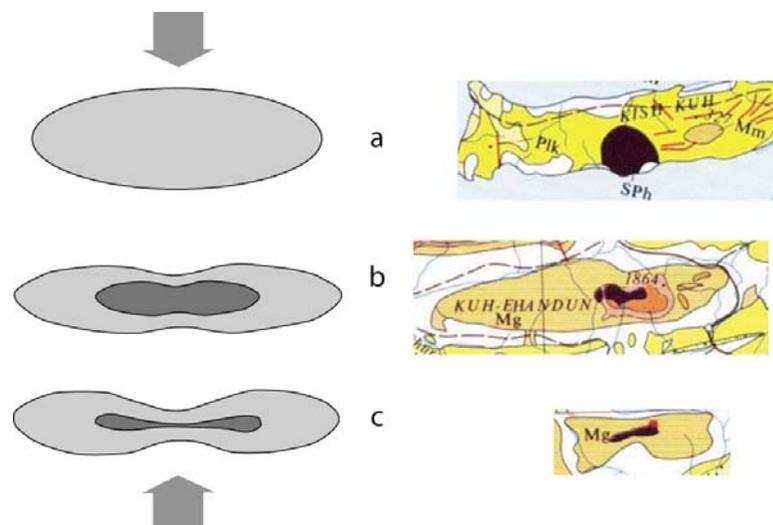
[40] At the end of the Paleozoic and during the Early Mesozoic, salt structures were already circular, as shown by the general rounded pattern of Hormuz salt diapir or domes offshore, showing that the evolution from salt ridges to salt diapirs did occur quite early. Some individual diapirs remain at or close to surface up to now, whereas others were buried under sediments, either before the Zagros folding event onshore or up to the present time offshore (Figure 13)

[*Jahani et al.*, 2007; *Letouzey et al.*, 2008] It is worth noting that on the basis of seismic images, draping over deeply buried circular diapirs is still active for some diapirs in the Persian Gulf. Moreover, they show that growing scenario could be different from one diapir to another, suggesting a control by welding of the salt layer at depth, and local load variation due to heterogeneous sedimentary supply. Permo-Triassic rifting along the Neo-Tethys margin did not greatly influence the growth of diapirs in the present southern gulf domain, whereas the Tertiary compressive events rejuvenated the salt ascent for most of the domes and a majority of which breached to the surface.

#### 5.1.2. Impact of Salt Structures on Zagros Folding

[41] Within the folded zone (ZFTB), in Central Zagros, emergent Hormuz diapir occurred along thrust faults and major wrench fault systems as the Kazerun Fault zone [*Talbot and Alavi*, 1996; *Bahrudi and Koyi*, 2003; *Letouzey and Sherkati*, 2004; *Sepehr and Cosgrove*, 2005; *Sherkati et al.*, 2006; *Callot et al.*, 2007; *Jahani et al.*, 2007; *Koyi et al.*, 2008]. On the contrary, in the Eastern Fars, there is no clear relationship between faults reaching the surface and salt extrusions, except in the interior Fars near the suture zone (Figure 1 and 2) [*Callot et al.*, 2007; *Jahani et al.*, 2007]. More precisely, the salt diapirs are located either near the pericline terminations of anticlines (48%), either in the core of the anticlines (18%) or along faults (29%). In few cases, diapirs emerge within synclines (5%) (Figures 1 and 2). We have to explain these different configurations and show how the presence of preexisting diapirs can explain some particularities of the Eastern Fars, i.e., the compact aspect ratio of folds and synclines and their frequent zigzag shape (Figures 1 and 2).

[42] Published sand box experiments have been used to study the role of preexisting diapirs during shortening [*Letouzey and Sherkati*, 2004; *Callot et al.*, 2007]. For the experimental procedures as well as the used scaling laws, the reader can refer to *Callot et al.* [2007]. These analog models with sand and silicone putty were designed to study the evolution of preexisting salt ridges and diapirs and their relationships with folds distribution. X-ray tomography has been used allowing the analysis of the kinematic evolution and the 3D geometries without interrupting or destroying the models [e.g., *Colletta et al.*, 1991]. The experiments show that during shortening, preexisting domes are squeezed, forcing silicone upward [*Letouzey et al.*, 1995; *Rowan and Vendeville*, 2006; *Callot et al.*, 2007]. The preexisting diapirs localize directly the incipient folds and thrusts as well as tear faults [*Letouzey and Sherkati*, 2004; *Callot et al.*, 2007]. The same models show that the shape of preexisting diapirs, i.e., either rounded diapirs or linear ridges, plays a major role in controlling the structural style, i.e., the shape of folds and the manner the diapirs will be involved within subsequent structures. In particular, diapirs with gentle dip generally act as ramps and remain in the footwall of the growing thrust whereas the incorporation of diapirs into the developing anticlines occurs rather when they had originally steep walls [*Callot et al.*, 2007]. Preexisting salt diapirs and walls thus have a primary role in the development of the fold-and-thrust belt, and we are



**Figure 14.** The general pattern of fold development on top of a preexisting diapir with a narrowing of the fold at the location of the squeezed diapir. (a) Namakdan, (b) Handun and (c) Ahmadi diapir cases (see *Callot et al.* [2007] for details).

going to illustrate this role using some detailed examples of geological features and with the help of analog models.

### 5.2. Preexisting Salt Diapirs and Geometry of Anticlines

[43] The Handun diapir situated along the cross section D (Figures 2 and 8d), is an example of a diapir located at the fold culmination. The nowadays eroded salt plug was located in the central part of the fold, which appears to be pinched out in map view (Figures 1 and 14). The Handun diapir is at present inactive with a wide empty crater but shows growth strata in the Eocene-Oligocene levels and recycled Hormuz materials in Miocene beds [*Jahani et al.*, 2007], which testify that the plug was near the surface before the Zagros orogeny and then emerged during folding. In such a context, the particular shape of the Handun fold can be explained: during deformation, strain was localized in the central zone, which was weakened by the presence of the salt plug (Figure 14b). This salt-cored anticline exhibits now a particular peanut-like shape, which is reproduced in analog models [*Callot et al.*, 2007] (Figure 14b). Lateral shortening of a dome is especially effective in triggering extrusion of the salt by erosion and the development of an allochthonous salt sheet or “Namakier” [e.g., *Jackson and Talbot*, 1991; *Jackson and Vendeville*, 1994, *Letouzey et al.*, 1995; *Rowan et al.*, 1999; *Jackson and Hudec*, 2005; *Rowan and Vendeville*, 2006; *Mohr et al.*, 2007] as observed in numerous salt plugs in Eastern Zagros [*Jahani et al.*, 2007]. Complete squeezing of the salt diapir leads to the formation of a local weld [*Rowan et al.*, 2001, 2003a, 2003b; *Rowan and Vendeville*, 2006] as shown in the core of several structures such as the Ahmadi anticline (Figure 2 and 14c).

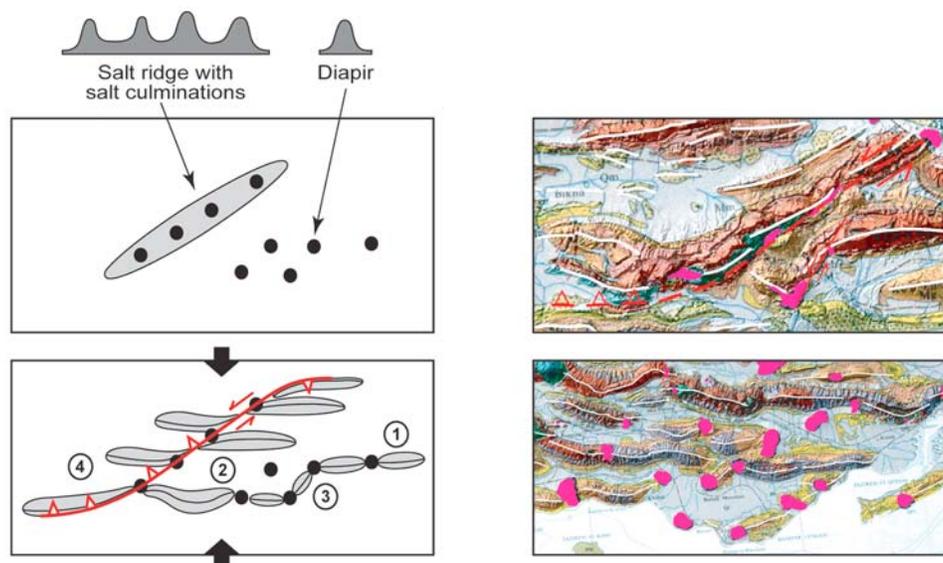
### 5.3. Preexisting Salt Diapirs and Fold Propagation

[44] At a glance, the folds in the eastern ZFTB present a large variety of shape, wavelength and fold axis direction (Figures 1 and 2) and are generally shorter and wider than

those observed where the ZFTB is devoid of salt diapirs. The Charak and Musallam anticlines represent examples of folds with diapirs near their terminations (Figures 1 and 2). Charak is a 60 km long E–W trending anticline restricted between the Kalat and Charak diapirs. The Musallam anticline is NE–SW trending 25 km long confined between Musallam and Champeh diapirs. *Rowan and Vendeville* [2006] suggested that such structures could result from the evolution of a salt wall under compression. Following analog experiments [*Rowan and Vendeville*, 2006], the two diapirs at the tips of the anticlines represent the remnants of a salt wall squeezed along the fold axis. However, in the studied examples, there is no evidence of squeezed salt wall or weld joining the diapirs. Therefore, we put forward another explanation. Refer to our analog experiments [*Callot et al.*, 2007], in which preexisting weak diapirs, localize deformation and initiate anticlines, that in turn propagate laterally to reach adjacent diapirs. Shortening in the cover is either accommodated by folding of the layered strata or by shrinkage of the diapir, which locally prevents the folding. This process can control the direction of the fold axis and the development of oblique folds as Musallam anticline, which is at about 45° to the regional shortening direction. On a general map (Figures 1 and 2), the changes in fold trends are underlined by a salt diapir. This suggests that the explanation given for Musallam can be extended at the scale of the eastern ZFTB. Other examples of such a zigzag shape are the Khamir and Pol anticlines that are controlled by Mijun, Khamir, and Pol salt diapirs (Figures 2 and 15).

### 5.4. Preexisting Salt Ridges and Surface Anticlines

[45] Harmadan, Khain, and Muran anticlines are located between cross sections C and D. They form together an 80 km long structure with a NE–SW trend punctuated by several preexisting salt diapirs along their southern limbs, in particular at their NE and SW terminations (Figures 1



**Figure 15.** General evolutionary sketch showing in map view. Figure 15 (bottom left) shows (1) lateral propagation of along preexisting salt diapirs, (2) preserved diapir in a syncline, (3) example of anticlines connecting salt diapirs, and (4) anticlines connected along a faulted oblique structure above a preexisting salt wall.

and 15, top right). *Leturmy et al.* [2009] emphasize smaller E–W folds, branching on the major structure. This is particularly spectacular at the southern termination of the structure, where the Harmadan anticline turns by  $45^\circ$  in map view and merges with an E–W fold. Considering the top of the Asmari Formation on both sides of the Harmadan-Khain-Muran structures, *Leturmy et al.* [2009] deduced a 750 m vertical step, which is indicative of an important reverse movement along a fault and suggest that the NE–SW trend fits a basement fault at depth cutting through a train of previously formed E–W folds.

[46] We propose as an alternative, that Harmadan, Khain and Muran anticlines correspond to a preexisting oblique salt wall, compare to the Zagros shortening direction, which has been shut during the Zagros orogeny (Figure 15). The main argument for this hypothesis is the existence of an almost continuous weld with remnant salt scars or diapirs at the tips of the structure. This pattern is similar to the structures presented by *Rowan et al.* [2001, 2003a, 2003b] in La Popa Basin (Mexico). A similar interpretation is proposed for the Khush-kuh anticline (Figures 1 and 2), which is cut out by an oblique right-lateral and reverse NE–SW basement fault. The fault is marked out by salt outcrops and a small fold at the eastern tip of the anticline. At larger scale, the same interpretation can be put forward for the two other giant folds, Jain and Faraghun, underlining the HZF in the area (Figures 1 and 2). In all cases, the surface geometry and the deduced cross section compare well to the squeezing of a preexisting salt wall (Figures 14).

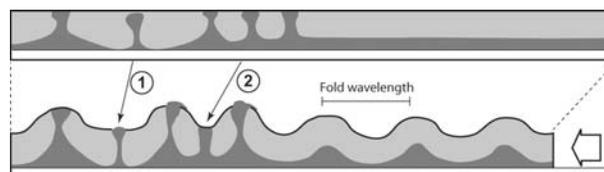
### 5.5. Forming Diapirs Within Synclines and Spacing of Folds

[47] Salt diapirs in the core of synclines such as the Do-Ao and Kalat-Bala (Figures 1 and 2) are less frequent. In both

cases interpreted seismic images display a local thickening of the horizons in adjacent synclines (down building due to salt migration from the salt source layer into the adjacent diapirs). In analog experiments we observed also that local thickening of sediments around salt diapirs prevents the propagation of an anticline toward the diapir. In fact, such a thickening induces a local rigidity, which prevents the fold initiation. The thick sedimentary pile increases the local rigidity and controls the spacing of anticlines which developed in adjacent areas where the pile is thinner. In other words, the local increase of subsidence due to the down building in the rim syncline adjacent to the diapir preclude it later incorporation into a fold (Figure 16). During folding, there is a kind of competition between the characteristic spacing of folds, depending mainly of the thickness of the stiff layers involved in folding [*Colletta et al.*, 1991], and the presence of diapirs along which the folds can nucleate (Figure 16). This can also explain some salt diapirs in the core of synclines or in the limbs of the fold.

## 6. Conclusion

[48] In southeastern Persian Gulf and Zagros Fold-and-Thrust Belt, as in Oman [*Peters et al.*, 2003], halokinesis



**Figure 16.** Forming diapirs within synclines are due either (arrow 1) to the local thickening of the horizons in adjacent synclines or (arrow 2) to the spacing of the preexisting diapirs compared to the characteristic fold wavelength.

began very early, i.e., soon after the deposition of salt, and developed up to the Present. This almost continuous halokinesis strongly influenced sedimentation with local uplift and downward during the whole Phanerozoic. This is illustrated by sedimentary thickness and facies changes in the lithostratigraphic pile around and above buried salt diapirs and, more generally, by the present configuration of the part of the Persian Gulf that is presently devoid of folds.

[49] As a consequence of this early halokinesis, ongoing folding in the Eastern Fars has been initiated in a region that was already punctuated by salt domes and diapirs. These preexisting salt diapirs and the associated sedimentary signatures, i.e., local thickening or thinning of lithostratigraphic units, strongly influenced the shape, localization, propagation and orientation of the folds as well as the spacing between them. In fact, the presence of the diapirs before any folding explains most of the particularities of the Eastern Fars, compared to other regions of the Zagros. In particular, and as also illustrated by our analog experiments (Figure 13), the position of the salt domes and ridges control the changes in direction of fold axes, giving birth to spectacular bended anticlines (Figures 1 and 2). The invocation of rotation about vertical axes or superimposed shortening episodes to explain such structures is consequently not necessary.

[50] As elsewhere in the ZFTB [Sherkati *et al.*, 2005; Molinaro *et al.*, 2005b; Sepehr *et al.*, 2006; Mouthereau *et al.*, 2007b] the tectonic style of the eastern Zagros is dominated by detachment folding above the Hormuz salt. However, contrarily to the Central Zagros [Sherkati *et al.*, 2006], only few local and minor intermediate detachment levels have been activated, namely in Middle Triassic and late Neogene levels. Compared to other regions of the Zagros, shortening along the cross sections presented in this paper (Figure 8) remains apparently low. One explanation could be that a quite important part of the shortening is accommodated by the “closure” of the diapirs, whose original width is not known precisely. Moreover squeezing diapir as a secondary effect of regional shortening is well illustrated by examples as the Handun fold (Figure 14).

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## References

- Agard, P., J. Omrani, L. Jolivet, and F. Mouthereau (2005), Convergence history across Zagros (Iran): Constraints from collisional an earlier deformation, *Int. J. Earth Sci.*, *94*, 401–419, doi:10.1007/s00531-005-0481-4.
- Alavi, M. (1994), Tectonics of the Zagros orogenic belt of Iran: New data and interpretation, *Tectonophysics*, *229*, 211–238, doi:10.1016/0040-1951(94)90030-2.
- Alavi, M. (2004), Regional Stratigraphy of the Zagros fold-thrust belt of Iran and its proforeland evolution, *Am. J. Sci.*, *304*, 1–20, doi:10.2475/ajs.304.1.1.
- Al-Siyabi, H. A. (2005), Exploration history of the Ara intrasalt carbonate stringers in the South Oman Salt Basin, *GeoArabia*, *10*, 39–72.
- Amthor, J. E., J. P. Grotzinger, S. Schröder, S. A. Bowring, J. Ramezani, M. W. Martin, and A. Matter (2003), Extinction of *Cloudina* and *Namacalathus* at the Precambrian-Cambrian boundary in Oman, *Geology*, *31*, 431–434, doi:10.1130/0091-7613(2003)031<0431:ECCANA>2.0.CO;2.
- Bahroudi, A., and H. A. Koyi (2003), Effect of spatial distribution of Hormuz salt on deformation style in the Zagros fold and thrust belt: An analogue modeling approach, *J. Geol. Soc.*, *160*, 719–733, doi:10.1144/0016-764902-135.
- Berberian, M. (1995), Master “blind” thrust faults hidden under the Zagros folds: Active basement tectonics and surface morphotectonics, *Tectonophysics*, *241*, 193–224, doi:10.1016/0040-1951(94)00185-C.
- Berberian, M., and G. C. P. King (1981), Towards a paleogeography and tectonic evolution of Iran, *Can. J. Earth Sci.*, *18*(2), 210–265, doi:10.1139/e81-019.
- Berberian, M., and D. Papastamatiou (1978), Khurgu (north Bandar Abbas, Iran), earthquake of March 21, 1977: A preliminary field report and a seismotectonic discussion, *Bull. Seismol. Soc. Am.*, *68*(2), 411–428.
- Beydoun, Z. R. (1991), Arabian plate hydrocarbon geology and potential—A plate tectonic approach, *AAPG Stud. Geol.*, *33*, 77 pp.
- Beydoun, Z. R. (1993), Evolution of the northeastern Arabian plate margin and shelf. Hydrocarbon habitat and conceptual future potential, *Rev. Inst. Fr. Pet.*, *48*, 311–345.
- Blanc, E. J. P., M. B. Allen, S. Inger, and H. Hassani (2003), Structural styles in the Zagros simple folded zone, Iran, *J. Geol. Soc.*, *160*, 401–412, doi:10.1144/0016-764902-110.
- Boote, D. R., D. D. Mou, and R. I. Waite (1990), Evolution of the Oman Tethyan Continental Margin structural evolution of the Suneinah Foreland, central Oman Mountains, in *The Geology and Tectonics of the Oman Region*, edited by A. H. F. Robertson, M. P. Searle, and A. C. Ries, *Geol. Soc. Spec. Publ.*, *49*, 397–418, doi:10.1144/GSL.SP.1992.049.01.25.
- Callot, J. P., S. Jahani, and J. Letouzey (2007), The role of pre-existing diapirs in fold and thrust belt development, in *Thrust Belt and Foreland Basin*, edited by O. Lacombe *et al.*, pp. 307–323, Springer, Berlin.
- Colletta, B., J. Letouzey, R. Pinedo, J. F. Ballard, and P. Bale (1991), Computerized X-ray tomography analysis of sand-box models: Examples of thin-skinned thrust systems, *Geology*, *19*, 1063–1067, doi:10.1130/0091-7613(1991)019<1063:CXRTAO>2.3.CO;2.
- Dahlstrom, C. D. A. (1969), Balanced cross sections, *Can. J. Earth Sci.*, *6*, 743–757.
- Edgell, H. S. (1996), Salt tectonics in the Persian Gulf basin, in *Salt Tectonics*, edited by G. L. Alsop, D. L. Blundell, and I. Davison, *Geol. Soc. Spec. Publ.*, *100*, 129–151, doi:10.1144/GSL.SP.1996.100.01.10.
- Falcon, N. L. (1969), Problems of the relationship between surface structures and deep displacements illustrated by the Zagros range, in *Time and Place in Orogeny*, edited by P. E. Kent, E. Satterthwaite, and A. M. Spencer, *Geol. Soc. Spec. Publ.*, *3*, 9–22, doi:10.1144/GSL.SP.1969.003.01.02.
- Falcon, N. (1974), Southern Iran: Zagros Mountains, in *Mesozoic Cenozoic Orogenic Belts: Data for Orogenic Studies*, edited by A. M. Spencer, *Geol. Soc. Spec. Publ.*, *4*, 199–211, doi:10.1144/GSL.SP.2005.004.01.11.
- Gansser, A. (1992), The enigma of the Persian dome inclusions, *Ecolage Geol. Helv.*, *85*, 825–846.
- Harrison, H. (1931), Salt domes in Persia, *J. Inst. Petrol. Technol.*, *17*, 300–320.
- Harrison, J. (1930), The geology of some salt-plugs in Laristan, southern Persia, *Q. J. Geol. Soc.*, *86*, 463–522, doi:10.1144/GSL.JGS.1933.086.01-04.18.
- Haynes, S. J., and H. McQuillan (1974), Evolution of the Zagros suture zone, southern Iran, *Geol. Soc. Am. Bull.*, *85*, 739–744, doi:10.1130/0016-7606(1974)85<739:EOTZSZ>2.0.CO;2.
- Hessami, K., H. A. Koyi, and C. J. Talbot (2001), The significant of strike-slip faulting in the basement of Zagros fold and thrust belt, *J. Pet. Geol.*, *24*, 5–28, doi:10.1111/j.1747-5457.2001.tb00659.x.
- Homke, S., J. Vergés, M. Garcés, H. Emami, and R. Karpuz (2004), Magnetotstratigraphy of Miocene–Pliocene Zagros foreland deposits in the front of the Push-e Kush Arc (Lurestan Province, Iran), *Earth Planet. Sci. Lett.*, *225*, 397–410, doi:10.1016/j.jeps.2004.07.002.
- Huber, H. (1975), Geological map of Iran 1:1,000,000 scale, Natl. Iranian Oil Co., Explor and Prod., Tehran.
- Hudec, M. R., and M. P. A. Jackson (2007), Terra infirma: Understanding salt tectonics, *Earth Sci. Rev.*, *82*, 1–28, doi:10.1016/j.earscirev.2007.01.001.
- Jackson, M. P. A., and M. R. Hudec (2005), Stratigraphic record of translation down ramps in a passive-margin salt detachment, *J. Struct. Geol.*, *27*, 889–911.
- Jackson, M. P. A., and C. J. Talbot (1991), A glossary of salt tectonics, *Geol. Circ.* *91-4*, 44 pp., Bur. of Econ. Geol., Univ. of Tex. at Austin, Austin.
- Jackson, M. P. A., and B. C. Vendeville (1994), Regional extension as a geologic trigger for diapirism, *Geol. Soc. Am. Bull.*, *106*, 57–73, doi:10.1130/0016-7606(1994)106<0057:REAAGT>2.3.CO;2.

- Jahani, S., J. Letouzey, and D. Frizon de Lamotte (2005), Fold, fault and Hormuz salt in the southern Zagros (Iran): Dehnow anticline as case study, paper presented at Earth Science Meeting, Geol. Soc. of Fr., Rueil-Malmaison, France.
- Jahani, S., J. P. Callot, D. Frizon de Lamotte, J. Letouzey, and P. Leturmy (2007), The salt diapirs of the eastern Fars province (Zagros, Iran): A brief outline of their past and present, in *Thrust Belt and Foreland Basin*, edited by O. Lacombe et al., pp. 287–306, Springer, Berlin.
- James, G. A., and J. G. Wynd (1965), Stratigraphic nomenclature of Iranian oil consortium agreement area, *AAPG Bull.*, 49, 2182–2245.
- Kent, P. E. (1958), Recent studies of south Persian salt diapirs, *AAPG Bull.*, 42, 2951–2972.
- Kent, P. E. (1970), The salt diapirs of the Persian Gulf region, *Trans. Leicester Liter. Philos. Soc.*, 64, 55–58.
- Kent, P. E. (1979), The emergent Hormuz salt diapirs of southern Iran, *J. Pet. Geol.*, 2, 117–144, doi:10.1111/j.1747-5457.1979.tb00698.x.
- Kent, P. E. (1987), Island salt diapirs in the Middle East and their tectonic implications, in *Dynamical Geology of Salt and Related Structures*, edited by I. Leiche and J. J. O'Brien, pp. 3–37, Academic, New York.
- Kent, P. E., and H. D. Hedberg (1976), Salt diapirism in southern Iran: A discussion, *AAPG Bull.*, 60, 458.
- Khattab, M. M. (1995), Interpretation of magnetic and gravity surveys in the southern Arabian Gulf, the Strait of Hormuz, and the northwestern most Gulf of Oman: Implications of pre-Permian basement tectonics, *Mar. Geol.*, 123, 105–116, doi:10.1016/0025-3227(95)80007-X.
- Koop, W. J., and R. Stoneley (1982), Subsidence history of the Middle East Zagros Basin, Permian to Recent, *Philos. Trans. R. Soc. London, Ser. A*, 305, 149–168, doi:10.1098/rsta.1982.0031.
- Koyi, H. A., A. Ghasemi, K. Hessami, and C. Diel (2008), The mechanical relationship between strike-slip faults and salt diapirs in the Zagros fold–thrust belt, *J. Geol. Soc.*, 165(6), 1031–1044, doi:10.1144/0016-76492007-142.
- Letouzey, J., and S. Sherkati (2004), Salt Movement, Tectonic Events, and Structural Style in the Central Zagros Fold and Thrust Belt (Iran), paper presented at 24th Annual GCSSEPM Foundation Bob F. Perkins Research Conference: Salt-Sediment Interactions and Hydrocarbon Prospectivity: Concepts, Applications, and Case Studies for the 21st Century, Gulf Coast Sect., Soc. for Sediment. Geol., Houston, Tex.
- Letouzey, J., B. Colletta, R. Vially, and J. C. Chermette (1995), Evolution of salt related structures in compressional setting, in *Salt Tectonics: A Global Perspective*, edited by M. P. A. Jackson, D. G. Roberts, and S. Snelson, *AAPG Mem.*, 65, 41–60.
- Letouzey, J., J. P. Callot, D. Pilot, S. Jahani, and C. Rigollet (2008), 4D modeling of inter-action between salt ridge, salt diapirs and folding: A new interpretation of the southern Zagros and offshore Iran structures, paper presented at AAPG Meeting, San Antonio, Tex.
- Leturmy, P., M. Molinaro, and D. Frizon de Lamotte (2009), Structure, timing and morphological signature of hidden reverse basement fault in the Fars arc of the Zagros (Iran), *Geol. Soc. Spec. Publ.*, in press.
- Loosveld, R. J. H., A. Bell, and J. J. M. Terken (1996), The tectonic evolution of interior Oman, *GeoArabia*, 1, 28–51.
- McQuarrie, N. (2004), Crustal scale geometry of the Zagros fold-thrust belt, Iran, *J. Struct. Geol.*, 26, 519–535, doi:10.1016/j.jsg.2003.08.009.
- McQuillan, H. (1991), The role of basement tectonics in the control of sedimentary facies, structural pattern and salt plug emplacements in the Zagros fold belt of south-west Iran, *J. Southeast Asian Earth Sci.*, 5, 453–463, doi:10.1016/0743-9547(91)90061-2.
- Mohr, M., J. K. Warren, P. A. Kukla, J. L. Urai, and A. Irmen (2007), Subsurface seismic record of salt glaciers in an extensional intracontinental setting (Late Triassic of northwestern Germany), *Geology*, 35(11), 963–966, doi:10.1130/G23378A.1.
- Molinaro, M., J. C. Guezou, P. Leturmy, S. A. Eshraghi, and D. Frizon de Lamotte (2004), The origin of changes in structural style across the Bandar Abbas syntaxis, SE Zagros (Iran), *Mar. Pet. Geol.*, 21(6), 735–752, doi:10.1016/j.marpetgeo.2004.04.001.
- Molinaro, M., H. Zeyen, and X. Laurencin (2005a), Lithospheric structure underneath the SE Zagros Mountains, Iran: Recent slab break-off?, *Terra Nova*, 17(1), 1–6, doi:10.1111/j.1365-3121.2004.00575.x.
- Molinaro, M., P. Leturmy, J.-C. Guezou, D. Frizon de Lamotte, and S. A. Eshraghi (2005b), The structure and kinematics of the southeastern Zagros fold-thrust belt, Iran: From thin-skinned to thick-skinned tectonics, *Tectonics*, 24, TC3007, doi:10.1029/2004TC001633.
- Motiei, H. (1993), *Stratigraphy of Zagros* (in Farsi), 536 pp., Geol. Surv. of Iran, Tehran.
- Motiei, H. (1995), *Petroleum Geology of Zagros, 1 and 2* (in Farsi), Geol. Surv. of Iran, Tehran.
- Mouthereau, F., O. Lacombe, J. Tensi, N. Bellahsen, S. Kargar, and K. Amrouch (2007a), Mechanical constraints on the development of the Zagros Folded Belt (Fars), in *Thrust Belt and Foreland Basin*, edited by O. Lacombe et al., pp. 246–266, Springer, Berlin.
- Mouthereau, F., J. Tensi, N. Bellahsen, O. Lacombe, T. De Boisgrollier, and S. Kargar (2007b), Tertiary sequence of deformation in a thin-skinned/thick-skinned collision belt: The Zagros Folded Belt (Fars, Iran), *Tectonics*, 26, TC5006, doi:10.1029/2007TC002098.
- Nilfouroushan, F. (2007), Displacement fields and finite strains in a sandbox model simulating a fold-thrust-belt, *Geophys. J. Int.*, 169, 1341–1355, doi:10.1111/j.1365-246X.2007.03341.x.
- Paul, A., A. Kaviani, D. Hatzfeld, J. Vergne, and M. Mokhtari (2006), Seismological evidence for crustal-scale thrusting in the Zagros mountain belt (Iran), *Geophys. J. Int.*, 166, 227–300, doi:10.1111/j.1365-246X.2006.02920.x.
- Peters, M. J., J. Filbrandt, J. Grotzinger, M. Newall, M. Shuster, and H. Al-Siyabi (2003), Surface-piercing salt domes of interior north Oman, and their significance of the Ara Carbonate “Stinger” hydrocarbon play, *GeoArabia*, 8(2), 231–270.
- Ricou, L. E. (1971), Le croissant ophiolitique périaire: Une ceinture de nappes mises en place au Crétacé supérieur, *Rev. Geogr. Phys. Geol. Dyn.*, 13, 327–350.
- Ricou, L. E. (1974), L'évolution géologique de la région de Neyriz (Zagros-Iranien et l'évolution structurale des Zagrides, these, Univ. Orsay, Orsay, France.
- Ricou, L., J. Braud, and J. H. Brun (1977), Le Zagros, *Mem. Soc. Geol. Fr.*, 8, 33–52.
- Rowan, M. G., and B. C. Vendeville (2006), Foldbelts with early salt withdrawal and diapirism: Physical model and examples from the northern Gulf of Mexico and the Flinders Ranges, Australia, *Mar. Pet. Geol.*, 23(9–10), 871–891, doi:10.1016/j.marpetgeo.2006.08.003.
- Rowan, M. G., M. P. A. Jackson, and B. D. Trudgill (1999), Salt-related fault families and fault welds in the northern Gulf of Mexico, *AAPG Bull.*, 83, 1454–1484.
- Rowan, M. G., T. F. Lawton, K. A. Giles, K. D. Hon, and K. S. Graff (2001), Anatomy of an exposed vertical salt weld, La Popa basin, Mexico, paper presented at AAPG Annual Meeting, Denver, Colo.
- Rowan, M. G., T. F. Lawton, and K. A. Giles (2003a), Variable expression of shortening along an exposed vertical salt weld, La Popa basin, Mexico, paper presented at AAPG International Conference and Exposition, Barcelona, Spain.
- Rowan, M. G., T. F. Lawton, K. A. Giles, and R. A. Ratliff (2003b), Near-salt deformation in La Popa basin, Mexico, and the northern Gulf of Mexico: A general model for passive diapirism, *AAPG Bull.*, 87, 733–756, doi:10.1306/01150302012.
- Sattarzadeh, Y., J. W. Cosgrove, and C. Vita-Finzi (1999), The interplay of faulting and folding during the evolution of the Zagros deformation belt, in *Forced Folds and Fractures*, edited by J. W. Cosgrove and M. S. Ameen, *Geol. Soc. Spec. Publ.*, 169, 187–196, doi:10.1144/GSL.SP.2000.169.01.14.
- Schoenherr, J., R. Littke, J. L. Urai, P. A. Kukla, and Z. Rawahi (2007), Polyphase thermal evolution in the Infra-Cambrian Ara Group (South Oman Salt Basin) as deduced by solid bitumen maturity, *Org. Geochem.*, 38, 1293–1318, doi:10.1016/j.orggeochem.2007.03.010.
- Schultz-Ela, D. D. (2003), Origin of drag folds bordering salt diapirs, *AAPG Bull.*, 87(5), 757–780, doi:10.1306/12200201093.
- Searle, M. P., C. J. Warren, D. J. Waters, and R. R. Parrish (2004), Structural evolution, metamorphism and restoration of the Arabian continental margin, Saih Hatat region, Oman Mountains, *J. Struct. Geol.*, 26, 451–473, doi:10.1016/j.jsg.2003.08.005.
- Sepehr, M., and J. W. Cosgrove (2005), Role of the Kazerun Fault Zone in the formation and deformation of the Zagros Fold-Thrust Belt, Iran, *Tectonics*, 24, TC5005, doi:10.1029/2004TC001725.
- Sepehr, M., J. Cosgrove, and M. Moieni (2006), The impact of cover rock rheology on the style of folding in the Zagros fold-thrust belt, *Tectonophysics*, 427, 265–281, doi:10.1016/j.tecto.2006.05.021.
- Setudehnia, A. (1973), The Paleozoic sequence at Zardkuh and Keh-e-Dinar, *Iranian Petrol. Inst. Bull.*, 60, 16–33.
- Setudehnia, A. (1978), The Mesozoic sequence in south-west Iran and adjacent areas, *J. Pet. Geol.*, 1, 3–34, doi:10.1111/j.1747-5457.1978.tb00599.x.
- Sharland, P. R., R. Archer, D. M. Casey, R. B. Davies, S. H. Hall, A. P. Howard, A. D. Hurbury, and M. D. Simmons (2001), *Arabian Plate Sequence Stratigraphy, GeoArabia Spec. Publ.*, vol. 2, Gulf Petro Link, Bahrain.
- Sherkati, S., and J. Letouzey (2004), Variation of structural style and basin evolution in the central Zagros (Izeh zone and Dezful Embayment), Iran, *Mar. Pet. Geol.*, 21, 535–554, doi:10.1016/j.marpetgeo.2004.01.007.
- Sherkati, S., M. Molinaro, D. Frizon de Lamotte, and J. Letouzey (2005), Detachment folding in the Central and eastern Zagros fold-belt (Iran): Salt mobility, multiple detachments and final basement control, *J. Struct. Geol.*, 27, 1680–1696, doi:10.1016/j.jsg.2005.05.010.
- Sherkati, S., J. Letouzey, and D. Frizon de Lamotte (2006), Central Zagros fold-thrust belt (Iran): New insights from seismic data, field observation, and sandbox modeling, *Tectonics*, 25, TC4007, doi:10.1029/2004TC001766.
- Stampfli, G. M., and G. D. Borel (2004), The TRANSMED transects in space and time: Constraints on the paleotectonic evolution of the Mediterranean domain, in *The TRANSMED Atlas: The Mediterranean Region From Crust to Mantle*, edited by W. Cavazza et al., pp. 53–90, Springer, Berlin.
- Stewart, S. A. (2007), Salt tectonics in the North Sea Basin: A structural style template for seismic interpreters, in *Deformation of the Continental Crust: The Legacy of Mike Coward*, edited by A. C. Ries, R. W. H. Butler, and R. H. Graham, *Geol. Soc. Spec. Publ.*, 272, 361–396, doi:10.1144/GSL.SP.2007.272.01.19.
- Stocklin, J. (1968), Structural history and tectonics of Iran: A review, *AAPG Bull.*, 52, 1229–1258.
- Stocklin, J. (1974), Possible ancient continental margin in Iran, in *Geology of the Continental Margin*, edited by C. A. Burk and C. L. Drake, pp. 873–887, Springer, New York.
- Stoneley, R. (1981), A review of petroleum source rocks in parts of the Middle East, in *Deformation of Sediments and Sedimentary Rocks*, edited by M. E. Jones and R. M. F. Preston, *Geol. Soc. Spec. Publ.*, 29, 263–269, doi:10.1144/GSL.SP.1987.026.01.18.
- Suppe, J. (1983), Geometry and kinematics of the fault-bend folding, *Am. J. Sci.*, 283, 684–721.

- Takin, M. (1972), Iranian geology and continental drift in the middle east, *Nature*, 235, 147–150, doi:10.1038/235147a0.
- Talbot, C., and J. M. Alavi (1996), The past of a future syntaxis across the Zagros, in *Salt Tectonics*, edited by G. L. Alsop, D. L. Blundell, and I. Davison, *Geol. Soc. Spec. Publ.*, 100, 89–109, doi:10.1144/GSL.SP.1996.100.01.08.
- Talebian, M., and J. Jackson (2004), A reappraisal of earthquake focal mechanisms and active shortening in the Zagros mountains of Iran, *Geophys. J. Int.*, 156, 506–526, doi:10.1111/j.1365-246X.2004.02092.x.
- Tatar, M., D. Hatzfeld, and M. Ghafory Ashtiani (2004), Tectonic of the Central Zagros (Iran) deduced from microearthquake seismicity, *Geophys. J. Int.*, 156, 255–266, doi:10.1111/j.1365-246X.2003.02145.x.
- Trusheim, F. (1960), Mechanism of salt migration in northern Germany, *AAPG Bull.*, 44, 1519–1540.
- Vendeville, B. C., and M. P. A. Jackson (1992), The rise of diapirs during thin-skinned extension, *Mar. Pet. Geol.*, 9(4), 331–354, doi:10.1016/0264-8172(92)90047-1.
- Vendeville, B. C., and K. T. Nilsen (1995), Episodic growth of salt diapirs driven by horizontal shortening, in *Salt Sediment and Hydrocarbons: GCSSEPM Foundation 16th Annual Research conference on Salt, Sediment and Hydrocarbons, December 3–6*, edited by C. J. Travis et al., pp. 285–295, Gulf Coast Sect., Soc. of Econ. Paleontol., Houston, Tex.
- Vendeville, B. C., H. Ge, and M. P. A. Jackson (1995), Scale models of salt tectonics during basement-involved extension, *Petrol. Geosci.*, 1, 179–183.
- Vergés, J., S. Homke, R. Karpuz, H. Osthus, M. Garcés, S. Grelaud, T. Nalpas, I. Sharp, H. Guadarzi, and H. Emami (2003), Integrated studies of the Zagros Mountain Front (southeast Lurestan, Iran): Structure and timing of deformation, paper presented at AAPG International Conference and Exhibition, Barcelona, Spain.
- Warburton, J., T. J. Burnhill, R. H. Graham, and K. P. Isaac (1990), The evolution of the Oman Mountain Foreland Basin, in *The Geology and Tectonics of the Oman Region*, edited by A. H. F. Robertson, M. P. Searle, and A. C. Ries, *Geol. Soc. Spec. Publ.*, 49, 419–427, doi:10.1144/GSL.SP.1992.049.01.26.
- Warrak, M. (1996), Origin of the Hafit structure: Implications for timing the Tertiary deformation in the northern Oman Mountains, *J. Struct. Geol.*, 18(6), 803–818, doi:10.1016/S0191-8141(96)80014-9.
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