

Structural variation along the Zagros and the nature of the Dezful Embayment

MARK B. ALLEN* & MORTEZA TALEBIAN†

*Department of Earth Sciences, University of Durham, Durham, DH1 3LE

†Research Institute for Earth Sciences, Geological Survey of Iran, PO Box 13185-1494, Tehran, Iran

Abstract - Structure varies along-strike in the Zagros fold and thrust belt of Iran, which is a principal element in the Arabia-Eurasia continental collision. Pre-collision, Late Cretaceous, ophiolite nappes (Kermanshah, Neyriz) and related nappes of deep marine sediments (Radiolarite Series) were emplaced next to two regions (Pusht-e Kuh arc, Fars) which later developed a consistent structural style across the range from the High Zagros Fault to the foreland limit of deformation. The intervening area has a zone of highly imbricated Arabian plate strata (the Bakhtyari Culmination) thrust southwest towards and over a low relief, low elevation region (the Dezful Embayment). There are no ophiolite nappes northeast of the Bakhtyari Culmination. Isopachs reflect these different structural patterns since the Late Cretaceous but not earlier. In the Late Cretaceous the Dezful Embayment recorded less deposition than adjacent areas to the northwest and southeast. In the Paleogene there was little net difference between the Dezful Embayment and its margins. The Dezful Embayment has been a depocentre since roughly 35 Ma, which is the likely time of initial collision between Arabia and Eurasia. We propose that the syn-collision structure and

1
2
3 stratigraphy of the Zagros is therefore strongly influenced by the variation in Late
4 Cretaceous ophiolite emplacement, but the original cause of this variation is not clear.
5
6
7
8
9

10 **1. Introduction**

11
12 This paper examines the nature of a low relief, low elevation area within the Zagros
13 fold and thrust belt in Iran: the Dezful Embayment (Figure 1). Together with the
14 Kirkuk Embayment in Iraq, it contains many of the important oil and gas fields of the
15 Middle East (Beydoun *et al.* 1992). However, despite over 100 years of exploration
16 and production, aspects of the Dezful Embayment's structure and stratigraphy are not
17 well-understood. This study aims to improve our knowledge of the region, by
18 integrating new observations from fieldwork and remote sensing with existing
19 geological and seismicity datasets. We focus on the Balarud Line that forms the
20 northern side of the Dezful Embayment, as its east-west orientation is unusual: most
21 structures in this part of the Zagros trend NW-SE (e.g. Hessami *et al.* 2001). The
22 origin and evolution of the Embayment cannot be understood without a wider
23 perspective of the Zagros structure. Therefore we also review the regional structure of
24 the Zagros, with the specific aim of determining the broader structural variation and
25 its causes and consequences.
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47

48 The Zagros mountains are present for ~2000 km between eastern Turkey and
49 southeast Iran (Figure 1). They are the geomorphic expression of the fold and thrust
50 belt that is the deformed passive continental margin of the Arabian plate (Beydoun *et*
51 *al.* 1992; Alavi, 1994; Berberian, 1995). Deformation continues in the active Arabia-
52 Eurasia collision zone. GPS-derived plate convergence vectors are roughly north-
53 south (Sella *et al.* 2002), and increase eastwards from 16 mm/yr at the apex of the
54
55
56
57
58
59
60

1
2
3 Arabian promontory to 26 mm/yr in eastern Iran (Vernant *et al.* 2004). NW-SE
4
5 trending folds and thrusts in the northwest Zagros combine with right-lateral strike-
6
7 slip faulting along the Main Recent Fault (MRF) to produce the overall north-south
8
9 convergence (Talebian & Jackson, 2002); this spatial separation of plate convergence
10
11 into thrust and strike-slip components is a good example of “strain partitioning”. In
12
13 the east of the range (Fars region; Figure 1) structures are more east-west trending,
14
15 orthogonal to the plate convergence vector. There is no range-parallel strike-slip
16
17 component in this region. Active shortening rates within the Zagros vary from 3-6
18
19 mm/yr in the western part of the range to 8 ± 2 mm/yr in the eastern part, determined
20
21 from GPS campaigns within the range (Hessami *et al.* 2006; Walpersdorf *et al.* 2006).
22
23
24
25
26
27
28

29
30 Several tectonic units are defined within the Zagros, although there is no
31
32 universal agreement on boundaries and nomenclature. The Arabia-Eurasia suture is
33
34 known as the Main Zagros Thrust (MZT), or Main Zagros Reverse Fault (MZRF),
35
36 and lies at the northeastern side of the Zagros. It is adjacent to the High Zagros, which
37
38 is the zone of highest elevations and deepest exposure levels: Cambrian and/or Upper
39
40 Precambrian strata are exposed. The High Zagros is conventionally shown as being
41
42 bounded to the southwest by the High Zagros Fault, a southwest-directed thrust. The
43
44 other main tectonic unit is the Simply Folded Belt (also known as the Simple Folded
45
46 Zone, or just the Folded Belt). This is present from the High Zagros Fault to the
47
48 Persian Gulf, or, onshore, to the frontal structures of the Zagros. It is characterised by
49
50 erosion down to Cretaceous or Oligocene-Miocene carbonates, in the prominent
51
52 whaleback anticlines that are striking geomorphic expressions of the Zagros structure.
53
54
55
56
57
58
59
60

2. Stratigraphy

1
2
3 The sedimentary cover of the northeastern side of the Arabian plate is commonly >10
4 km thick in total, although this is based largely on estimates from gravity and
5
6 magnetic data (e.g. [Morris, 1977](#); Yousefi and Friedberg, 1978). Exposure levels and
7
8 well data typically only reveal the top few kilometres of this stratigraphy. The
9
10 exposure level is rarely deeper than the Cretaceous.
11
12
13
14
15
16
17

18 Stratigraphy in the Zagros (Figure 2) records the evolution from the passive
19 margin of the Arabian plate to the foreland basin of the Arabia-Eurasia collision zone,
20 although the precise time of the onset of continental collision is debated. Common
21 estimates are the Late Eocene (~35 Ma; e.g. [Vincent et al. 2005](#); Allen & Armstrong,
22 2008; [Ballato et al. in press](#)) and the Early Miocene (~20 Ma; e.g. [Okay et al. 2010](#)),
23 or even later (e.g. [Guest et al., 2006](#)). Precambrian basement is not exposed in situ,
24 but recorded as blocks brought to the surface in salt diapirs (Kent, 1979), derived
25 from the Hormuz Series. The Hormuz Series is of late Precambrian/Cambrian age,
26 and overlies the basement. The Series is present across a wide area of the Zagros and
27 Middle East (Edgell, 1991) and contains thick evaporites, mainly halite ([Talbot &](#)
28 [Alavi, 1996](#)). The original distribution of these evaporites is not known. Some
29 geologists (e.g. [Murriss, 1980](#); Edgell, 1991) infer that the present distribution of
30 diapirs is a guide to the original depositional extent: these occur across large areas of
31 the eastern Zagros (Fars), but not within the Dezful Embayment or further west
32 (Figure 1). Hormuz Series salt also crops out in the High Zagros to the north of the
33 Embayment ([National Iranian Oil Company \(NIOC\), 1977a](#)). Areas without salt
34 exposures were regions of clastic deposition or non-deposition in such schemes. Other
35 studies extend the distribution of evaporites throughout the Zagros ([Talbot & Alavi,](#)
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 1996), with later factors controlling its present distribution in diapirs (e.g. Kent, 1979;
4
5 Carruba *et al.* 2006).
6
7
8
9

10 The Hormuz Series lies at the base of a Palaeozoic platform succession. This
11 is inferred to be interrupted by Permian rifting, that led to the spreading of the Neo-
12 Tethyan Ocean from the contemporary margin of Gondwana (Şengör *et al.* 1988),
13 although the evidence on which this is based remains sparse (Szabo & Kheradpir,
14 1978). Sepehr & Cosgrove (2004) illustrate examples of a Permian-Triassic half
15 graben from the Dezful Embayment. A ~4-5 km thick Mesozoic and lower Tertiary
16 succession contains alternating deposits of clastics and carbonates (Setudehnia, 1978,
17 Sherkati & Letouzey, 2004; Farzipour-Saein *et al.* 2009; Homke *et al.* 2009). Mid
18 Cretaceous (Bangestan Group) and Oligo-Miocene (Asmari) limestones form
19 prominent topographic markers in the Zagros landscape, by virtue of their high
20 mechanical strength and consequent low erosion rates. The equivalent stratigraphy in
21 the sub-surface of the Dezful Embayment contains a sandstone unit, the Ahwaz
22 Member (Motiei, 1993; Sharland *et al.* 2001). Gachsaran Formation evaporites
23 (Miocene) form a second mobile unit in the stratigraphy (O'Brien, 1957; Sherkati &
24 Letouzey, 2004), below a Miocene-Quaternary clastic succession that coarsens
25 upwards (Homke *et al.* 2004). These clastics are divided in to two main non-marine
26 units, the Agha Jari and Bakhtyari formations, above a marine unit, the Mishan
27 Formation (Figure 2). The age of the Bakhtyari Formation was tentatively assigned to
28 the Pliocene (James & Wynd, 1965) although age-diagnostic fossils are rare. Recent
29 work (Fakhari *et al.* 2008) has demonstrated that outcrops in the northeast of the
30 Zagros originally mapped as Bakhtyari Formation are as old as Early Miocene and
31 possibly Oligocene. Thus this unit is strongly diachronous, and schemes invoking a
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 regional, orogen-wide pulse of deformation in the Pliocene and a synchronous
4
5 unconformity at the base of the Bakhtyari Formation (e.g. Falcon, 1974; Carruba *et al.*
6
7 2006) should be treated with caution.
8
9

10 11 12 13 **3. Structure**

14
15 This section is in three parts. First, we describe the seismicity of the Dezful
16
17 Embayment, as the earthquakes provide valuable information on the sub-surface
18
19 structure that cannot be obtained by other means. Second, we describe the structure of
20
21 the Embayment based on published accounts of the exposed and sub-surface geology,
22
23 and our own field observations. Finally, we review the wider structure of the Zagros,
24
25 with the particular aim of highlighting those features that vary along strike and may
26
27 bear on the origin of the Embayment itself.
28
29
30
31
32
33

34 **3.a. Seismicity**

35
36 The instrumental earthquake record shows relatively intense seismicity within the
37
38 Embayment compared with adjacent areas. This is allowing for a typical 20 km
39
40 uncertainty in epicentre locations (Talebian & Jackson, 2004). Figure 3 shows focal
41
42 mechanisms from the Harvard seismicity catalogue
43
44 (<http://www.globalcmt.org/CMTsearch.html>) and Talebian & Jackson (2004) and
45
46 references therein. Events are typically steep-dipping thrusts ($>30^\circ$), although it is not
47
48 always possible to determine the real nodal plane. Focal depths range from a few
49
50 kilometres to 20 km, especially deeper in the north. There is an uncertainty in these
51
52 values of ± 4 km. Down-dip rupture length for an $M 5$ event is typically 4 km and for
53
54 $M 6$, 12 km, therefore if an event of $M 5-6$ is at 20 ± 4 km it will rupture at 20 km,
55
56 even if the true hypocentre is as shallow as 16 km (Maggi *et al.*, 2000).
57
58
59
60

1
2
3
4
5
6 Most events are located between the Dezful Embayment Fault and the
7
8 Mountain Front Fault (Figure 3) where topography is steepest. Higher regions (>1000
9
10 m elevation) to the northeast are less seismically active, although there are two
11
12 oblique and strike-slip events recorded close to the Main Recent Fault and the
13
14 Kazerun Line. One thrust earthquake took place close to the High Zagros Fault. Three
15
16 events occurred close to the frontal anticlines of the Dezful Embayment, suggesting
17
18 that these folds are underlain by thrusts similar to the structures further northeast.
19
20
21
22
23
24

25 Combining the earthquake depths with depth-to-basement maps confirms that
26
27 in places the Zagros basement is actively thrusting (Jackson, 1980; Berberian, 1995;
28
29 Maggi *et al.*, 2000; Talebian & Jackson, 2004; Tatar *et al.* 2004), but at the same time
30
31 some seismogenic faulting occurs purely within the sedimentary cover (Koyi *et al.*
32
33 2000; Adams *et al.* 2009). There is no difference in the orientation, magnitude or dip
34
35 of events rupturing within the cover or basement, or both. There is some evidence for
36
37 low angle (<20° dip) thrusting in the seismicity record, especially in the northeast of
38
39 the Embayment, for example the 19th October 1980 event at 32.70° N 48.58° E at 17
40
41 km depth (Maggi *et al.*, 2000). Other low angle slip is likely to happen aseismically,
42
43 perhaps along weak detachment horizons (Casciello *et al.* 2009).
44
45
46
47
48
49
50

51 **3.b. Dezful Embayment structure**

52 The Dezful Embayment is a trapedzoidal area within the Zagros **Simply Folded Belt**
53
54 (Figure 3), covering ~75,000 km². Isopachs for the Dezful Embayment show >5000 m
55
56 of Cenozoic strata in the northeast of the region (Figure 4a), predominantly Miocene-
57
58 Quaternary non-marine clastics, although the details vary between different sources
59
60

1
2
3 (Koop & Stoneley, 1982; Motiei, 1993; Bahroudi & Talbot, 2003; Carruba et al.,
4
5
6 2006). Adjacent areas have far thinner successions over this interval, consistent with
7
8 the Embayment being a depocentre within the Arabia-Eurasia collision zone. Precise
9
10 ages are not known for large parts of this basin fill. Oligocene and Lower Miocene
11
12 strata (Asmari Limestone and lateral equivalents) show differential subsidence
13
14 patterns, with 600-900 m within the Embayment and only 200-400 m thickness
15
16 outside of it (Figure 4b). The Paleocene-Eocene succession is of similar thickness in
17
18 the north of the Embayment and adjacent areas of the Pusht-e Kuh arc: ~100 m (not
19
20 shown).
21
22
23
24
25
26

27 Upper Cretaceous isopachs show a thin succession (<200 m) across the Dezful
28
29 Embayment, in contrast to thicker accumulations to the northwest and southeast (1500
30
31 m and 500 m respectively; Figure 4c). Lower Cretaceous and Jurassic isopachs show
32
33 no consistent difference between the Embayment and surrounding areas (Figure 4d).
34
35 Some Cretaceous activity along the Kazerun Fault is suggested by local isopach
36
37 variations in this region (Sephehr & Cosgrove, 2004). To summarise these data,
38
39 isopachs of Upper Cretaceous and Oligocene-Quaternary strata change across the
40
41 Line (Figure 4), indicating a pre-Cenozoic and pre-collision history to the structure
42
43 (Motiei, 1993), as well as an Oligocene-Quaternary difference. Differences are not so
44
45 apparent in the pre-Late Cretaceous and Paleocene-Eocene intervals.
46
47
48
49
50
51
52

53 The northeast boundary of the Dezful Embayment is the Mountain Front Fault
54
55 (or Flexure), which is a step in the structural relief of several km (Berberian, 1995),
56
57 and possibly as much as 6 km at Kuh-e Kamar Meh (Figures 3, 5 and 6a). The
58
59 southwest boundary occurs along anticlines roughly in alignment with Zagros frontal
60

1
2
3 structures to the northwest and southeast (Figure 1). The eastern limit to the
4
5 Embayment is the Kazerun Fault (Figure 3), which is one of a series of right-lateral
6
7 strike-slip faults that trend NNW-SSE through the Zagros at around longitudes 51-
8
9 52°E (Kareh Bas, Sabz Pushsan and Sarvestan; Figure 1; Authemayou *et al.* 2006).
10
11 Exposure levels on the eastern side of the fault are consistently deeper than to the
12
13 west (typically Cretaceous versus Asmari Limestone). The offset of the fault is on the
14
15 order of 10 km (Authemayou *et al.* 2006). There is another, less clear-cut north-south
16
17 structure west of the Kazerun Line, the Izeh Line (Figure 3), but less is known about
18
19 the structure of this feature. It also has structural relief across it. Exposure levels are
20
21 typically down to the Asmari Limestone to its east and within the Gachsaran
22
23 Formation or younger units to its west. This is an important factor in the regional
24
25 hydrocarbon geology, as the Gachsaran Formation is an effective seal. It is part of the
26
27 explanation why oil and gas fields are concentrated to the west of the Izeh Line. The
28
29 northern limit of the Dezful Embayment is the Balarud Line (Figure 7). Cretaceous
30
31 strata are exposed in the anticlines to the north in the Pusht-e Kuh arc. We examine
32
33 this feature in some detail, because its structure is less well-understood than the other
34
35 margins of the Embayment.
36
37
38
39
40
41
42
43
44
45

46 The east-west trend of the Balarud Line is an unusual orientation for a
47
48 structure in the Zagros (Figures 1 and 3; Bahroudi & Koyi, 2004). The Balarud Line
49
50 has been mapped as a left-lateral strike-slip fault (Berberian, 1995; Hessami *et al.*
51
52 2001), based on the apparent displacement of folds in its vicinity, such as Siah Kuh
53
54 (Figure 7). However, none of the major, well-constrained, earthquakes in the vicinity
55
56 are strike-slip events (Talebian & Jackson, 2004; see previous section on seismicity).
57
58 One event (2nd April 1989, 32.66° N 47.78° E) has a possible left-lateral focal plane,
59
60

1
2
3 but the Harvard CMT solution is based on a 37% double-couple – much less than the
4
5 70% usually taken for a reliable solution. An inferred left-lateral slip of 120-130 km
6
7
8 (Hessami *et al.* 2001; Bahroudi & Koyi, 2003) is based on the apparent offset of the
9
10 Mountain Front Fault, but this is arguably the distance between the southwestern
11
12 exposures of the Asmari Limestone north and south of the Balarud Line. There is no
13
14 evidence that an originally contiguous fault has been displaced.
15
16
17
18
19

20 The structure in the region consists of anticlines that trend northwest-
21
22 southeast, and plunge towards the Line (Figure 7). Some individual fold traces are
23
24 deflected towards an east-west orientation as they approach the Line. Two of the folds
25
26 on the south side, within the Embayment, possess a roughly east-west orientation
27
28 (Kabud and Balarud). None of the folds can be mapped across the Line, offset or not.
29
30 Field relations show the plunge of the folds as they approach the Line from one side
31
32 or the other. Figure 6b shows the abrupt southeast termination of the Kabir Kuh
33
34 anticline, which runs for >200 km to the northwest, but plunges and dies out over a
35
36 lateral distance of 3 km, adjacent to the Balarud Line. Figure 6c shows an equivalent
37
38 view of the Kuh-e Chenareh anticline, which is the next fold to the east of Kabir Kuh
39
40
41 (Figure 7).
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

To summarise, there is no strong geological or geomorphic evidence for the
existence of an active, emergent fault along the Balarud Line, of whatever motion
sense. Nor do the seismicity data indicate an active fault with an east-west trend
(Figure 3). However, the Balarud Line exerts a strong control on the tips of folds to
either side of it, which needs to be explained. Isopach data show the different
sedimentary thicknesses on either side of the Balarud Line (Figure 4), which implies a

1
2
3 step in the surface of the basement; the Line must separate more deeply buried
4
5 basement within the Embayment from equivalent rocks to the north. Sedimentary
6
7 horizons must likewise be present at different depths, although the very variable
8
9 Cenozoic stratigraphy means that a particular unit found within the Embayment may
10
11 not be present to its north in the same form, if at all. We suggest that this contrast and
12
13 discontinuity in the basement and cover succession has prevented folds and thrusts
14
15 from propagating laterally across it, leading to the situation where folds terminate
16
17 along the Balarud Line, without necessarily being offset by slip along it. A steeply-
18
19 dipping, east-west trending fault does not have a favourable orientation to slip during
20
21 the north-south plate convergence of the Arabia-Eurasia collision, but the presence of
22
23 such a discontinuity may well affect the active folds and thrusts to its north and south.
24
25 This is an explanation for why the Balarud Line behaves as it does at present. It does
26
27 not answer the question of why different successions accumulated on either side of it
28
29 from the Late Cretaceous onwards, which we address in a later section.
30
31
32
33
34
35
36
37
38

39 Northwest-southeast trending anticlines dominate the internal structure of the
40
41 Embayment (Figure 3). Exposure levels deepen from southwest to northeast, such that
42
43 the frontal structures expose Upper Miocene – Quaternary clastics mapped as Agha
44
45 Jari and Bakhtyari formations. West of the Izeh Line, evaporites of the Gachsaran
46
47 Formation crop out northeast of the Dezful Embayment Fault (Figure 6d; Berberian,
48
49 1995); this step in the exposure level indicates a significant thrust within the
50
51 Embayment. Only Kuh-e Asmari (Figure 3) exposes the Asmari Limestone west of
52
53 the Izeh Line and southwest of the Mountain Front Fault. East of the Izeh Line there
54
55 is a more rapid deepening of exposure level northwards from the coastal anticlines
56
57
58
59
60 (Sherkati & Letouzey, 2004).

1
2
3
4
5
6 The typical sub-structure of the anticlines is largely known from limited well
7
8 and seismic data (Sepéhr & Cosgrove, 2004; Carruba *et al.* 2006): the moderate
9
10 exhumation precludes direct observation of dissected folds. Structures are
11
12 complicated by the Gachsaran Formation evaporites decoupling the structure above
13
14 and below their level (Sherkati & Letouzey, 2004; Sherkati *et al.* 2005; Carruba *et al.*
15
16 2006). Where the unit is still buried it acts as a detachment zone, such that overlying
17
18 sediments may be folded in to relatively simple, coherent anticlines, but the fold axes
19
20 are displaced by a few km to the southwest with respect to fold crests within the
21
22 underlying strata. Where the Gachsaran Formation is exposed it has flowed, leading to
23
24 more complex structures within and below the unit and disharmonic relationships
25
26 between the folds above and below the evaporites (Sherkati *et al.* 2005; Figure 5).
27
28
29
30
31
32
33

34 It is a long-standing issue of Zagros geology to what degree, if any, thrusts cut
35
36 the basement. Some work suggests major basement involvement (Jackson, 1980;
37
38 Ameen, 1992), but other papers show essentially complete detachment within the
39
40 sedimentary cover (McQuarrie, 2004). There are also papers that suggest a mixture of
41
42 the two structural styles (Blanc *et al.* 2003; Mouthereau *et al.* 2007) or a development
43
44 from initial thin-skinned to later thick-skinned geometries (Molinaro *et al.* 2005). See
45
46 Ahmadhadi *et al.* (2007) for a detailed field-based study of evidence for basement
47
48 involvement in the early stages of Zagros deformation. As described in section 3.a.,
49
50 the Zagros seismicity record clearly shows at least some basement thrusting (Tatar *et*
51
52 *al.* 2004; Talebian & Jackson, 2004), and that there is no difference in dip or strike
53
54 between the deepest and shallowest events of $M > 5$. We use this seismicity constraint
55
56 with the exposed geology and sub-surface constraints, to generalise the fold and fault
57
58
59
60

1
2
3 structure within the Dezful Embayment (Figure 5). We envisage that the typical
4
5 thrusts within the Embayment are planar and relatively steep, and typically link
6
7 through the sedimentary cover to the basement. They are plausibly inversions of the
8
9 Permian rift faults of the Arabian margin (Sepehr & Cosgrove, 2004), and this is
10
11 indicated schematically on Figure 5. This is speculative, but consistent with the
12
13 earthquake data and the sub-surface data of Sepehr & Cosgrove (2004). The inferred
14
15 fault spacing is 10-20 km (Figure 5), which is also consistent with inverted
16
17 continental rifts (Jackson, 1980). Such planar fault geometries for the main thrusts do
18
19 not rule out detachments operating within the sedimentary cover. Detachments are
20
21 conclusive within the Gachsaran Formation within the Embayment, and highly likely
22
23 at deeper levels (Carruba et al., 2006). However, the Hormuz Series evaporites have
24
25 not been proven in the sub-surface of the Dezful Embayment, and so we do not depict
26
27 major detachment at the base of the sedimentary succession (Figure 5). It is
28
29 geometrically possible that folds do detach at this level, either on the Hormuz Series
30
31 salt (Carruba et al., 2006) or a lateral shale equivalent (McQuarrie, 2004), but Figure
32
33 5 offers an alternative model.
34
35
36
37
38
39
40
41
42

43 The Hormuz Series definitely plays a role northeast of the High Zagros Fault,
44
45 where it crops out associated with thrust slices that exhume the Palaeozoic
46
47 stratigraphy but not the basement. This region is therefore more likely to have a major
48
49 detachment along the Hormuz Series rocks, with the underlying basement underthrust
50
51 beneath the Sanandaj-Sirjan Zone of Central Iran. The structure close to the suture
52
53 zone is cross-cut by the active, right-lateral Main Recent Fault, which has two strands
54
55 in this area (Authemayou *et al.* 2006).
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Total crustal thickness under the Zagros has recently been constrained by teleseismic receiver function analysis to be 42 ± 2 km, only thickening to ~55-70 km close to the Main Zagros Reverse Fault (Paul et al., 2010). This result has the implication that the Zagros crust is not significantly thicker than the foreland of the Arabian plate, which also has a crustal thickness of ~40 km (Gok et al., 2008).

3.c. Regional structure

The previous section made the observation that something has made the Dezful Embayment have a different subsidence record from adjacent areas in the Late Cretaceous and the Oligocene-Recent. This section addresses the regional structure, and proposes an explanation for the structural and stratigraphic variation.

North of the Dezful Embayment, the **Simply Folded Belt** and High Zagros are collectively known as the Pusht-e Kuh arc (Figure 1). This is commonly shown as a salient between the Dezful Embayment and the Kirkuk Embayment further north (Bahroudi & Koyi, 2003), although as noted the frontal structures of the Pusht-e Kuh arc are roughly aligned with the frontal structures to the northwest and southeast (Figure 1). Structural style across the **Simply Folded Belt** in the Pusht-e Kuh arc is more uniform than an equivalent transect across the Dezful Embayment and the zone to its northeast, the Bakhtyari Culmination (e.g. Farzipour-Saein *et al.* 2009; Figure 5). Structures close to the range front exhume the Cretaceous carbonates, and this level of exposure is maintained across the remainder of the **Simply Folded Belt** to the northeast, or becomes shallower, exposing the Oligocene-Miocene limestones. There is a sharp contrast in geology at the High Zagros Fault, which thrusts Cretaceous deepwater marine sediments, known as the Radiolarite Series, to the southwest

1
2
3 (Homke *et al.* 2009). Higher nappes include at least two ophiolite slices (collectively
4 known as the Kermanshah ophiolite; Ghazi & Hassanipak, 1999), and an
5
6 allochthonous slice of Upper Triassic-Cretaceous limestones: the Bisotun Limestone
7
8 (NIOC, 1978; Agard *et al.* 2005). An alternative explanation for the structure in this
9
10 region is that the ophiolites belong to a single sheet, folded beneath an overlying
11
12 thrust sheet (Mohajjel *et al.* 2003). There are no Lower Palaeozoic strata and no
13
14 Hormuz Series evaporites exposed in this region. The highest, sub-horizontal, nappes
15
16 are derived from the Sanandaj-Sirjan Zone, i.e. they originated on the Eurasian side of
17
18 the suture (Agard *et al.* 2005). The suture is the thrust plane below this pile of
19
20 Eurasia-derived nappes. Overall, the High Zagros is ~40 km across in this region. The
21
22 structure is complicated by the Main Recent Fault, which cuts through the low angle
23
24 thrusts and nappes in this area (Talebian & Jackson, 2002).
25
26
27
28
29
30
31
32
33

34 To the northeast of the Dezful Embayment, the remainder of the Simply
35
36 Folded Belt is ~40 km wide, and is overthrust by imbricated strata of the Arabian
37
38 plate at the High Zagros Fault (Figure 5). Collectively this mountainous, highly
39
40 deformed area is known as the Bakhtyari Culmination (Figures 1 and 5). Thrust sheets
41
42 northeast of the High Zagros Fault expose the stratigraphy down to the Cambrian, and
43
44 the Hormuz Series salt is exposed along fault traces (Authemayou *et al.* 2006). The
45
46 High Zagros is only 25-40 km wide in this region, before the Main Zagros Reverse
47
48 Fault is reached. There are no ophiolites or Radiolarite Series rocks along or
49
50 southwest of this part of the suture; Eurasian plate rocks on the northeast side are
51
52 mapped as metamorphics, and are overlain unconformably by Cretaceous carbonates
53
54 (NIOC, 1975).
55
56
57
58
59
60

1
2
3 The structure of the Zagros, especially the High Zagros, is different again
4 across the Fars region to the east and southeast of the Dezful Embayment
5
6 (Mouthereau *et al.* 2007; Figure 1). Anticlines in the **Simply Folded Belt** typically
7
8 exhume strata as deep as the Cretaceous Bangestan Group. Permian strata are exposed
9
10 at Kuh-e Surmeh (Figure 1), but this is an unusual structure, as it is at the end of a
11
12 strike-slip fault (Mouthereau *et al.* 2006). There is no consistent northwards increase
13
14 in the amount of exhumation across the **Simply Folded Belt** (NIOC, 1977). Some of
15
16 the most extensive exposures of Cretaceous strata occur in the southern folds, which
17
18 are also the highest topographic ranges. The High Zagros Fault is mapped at the
19
20 southern edge of the regional exposure of Cretaceous strata (Berberian, 1995), but this
21
22 is less of a clear-cut boundary than is depicted on summary tectonics maps. It is not
23
24 the absolute southern exposure of Cretaceous strata, nor is it the northern limit of
25
26 Tertiary strata within anticline cores. Within the High Zagros of Fars there is no
27
28 discernible difference in structural style from the **Simply Folded Belt** to its south:
29
30 whaleback anticlines exhume down to the Bangestan Group. The northeast side of the
31
32 High Zagros is more variable. In some places the Cretaceous-cored anticlines occur
33
34 up to the line of the Main Zagros Reverse Fault, which juxtaposes them against
35
36 metamorphic basement of the Sanandaj-Sirjan Zone to the northeast. But, there is also
37
38 the Neyriz ophiolite complex and associated Radiolarite Series rocks (Babaie *et al.*
39
40 2006), which are emplaced to the southwest, over the Cretaceous passive margin
41
42 strata (Figure 1). Southeast of the main ophiolite outcrop, there is a salient of the
43
44 Sanandaj-Sirjan Zone of Central Iran (Figure 1), where low grade metamorphic rocks
45
46 are thrust southwest over the Arabian plate stratigraphy (NIOC, 1977).
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 The above account of the regional geology of the Zagros demonstrates that
4 lateral differences across the Iranian sector of the **Simply Folded Belt** (Pusht-e
5 Kuh/Dezful Embayment/Fars) have counterparts in variations in the structure and
6 stratigraphy of the High Zagros and suture zone. Given this variation, it is possible to
7 look for clues to the origin of the Dezful Embayment. Key points are 1) The Late
8 Cretaceous was the first time that different sedimentary thicknesses clearly distinguish
9 the Embayment from surrounding areas; 2) the Late Cretaceous saw a thinner
10 sedimentary succession over the Embayment than surrounding areas, but the
11 Cenozoic, especially Late Cenozoic, strata are thicker; 3) Significant ophiolite nappes
12 are present north and south of the Embayment, but not within the Bakhtyari
13 Culmination, across strike from the Embayment itself.
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31

32 Late Cretaceous isopach variation may be explained as follows. Ophiolite and
33 associated nappe emplacement over the Pusht-e Kuh arc and Fars region generated
34 greater contemporary subsidence in front of those nappes, compared with the
35 intervening Dezful Embayment – hence the Late Cretaceous isopach variations
36 (Figure 4d). This model raises the question of why ophiolite emplacement varied
37 spatially, which is hard to answer, but is common along other continental collision
38 zones (Cawood & Suhr, 1992). A possible scenario is an Arabian plate promontory at
39 the future Bakhtyari Culmination, leading to the generation and rapid emplacement of
40 ophiolitic lithosphere at the adjacent embayments along the leading edge of Arabian
41 plate. This is similar to the model proposed for Caledonian ophiolite generation in the
42 Caledonides (Cawood & Suhr, 1992). During subsequent continental collision, such a
43 promontory would focus deformation within the Arabian plate, leading to the present
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 imbrication of the Bakhtyari Culmination and the rapid subsidence of the Dezful
4 Embayment in front of it.
5
6
7
8
9

10 **4. Geomorphology**

11 Anticlines within the Dezful Embayment coincide with modest topographic highs,
12 generally only a few 10s of metres above the surrounding plains, which are
13 themselves only a few metres above sea level (Figure 8). Upper Cenozoic clastics
14 assigned to the Agha Jari and Bakhtyari formations (Figure 2) are exposed at the fold
15 crests. The fossil-poor, terrestrial nature of these units means that assignments are
16 done on mainly on the basis of the lithologies, with little biostratigraphic control
17 (James & Wynd, 1965). This practice means that some of the finer-grained strata
18 assigned to the Agha Jari Formation are potentially time equivalent to coarser strata
19 mapped as Bakhtyari Formation. The Ahwaz structure (Figure 3) is an example of
20 this: the uppermost exposed strata along the fold crest are mapped as Agha Jari
21 Formation (NIOC, 1975), which, if a strict layercake stratigraphy applies, suggests
22 that the fold has uplifted, exhumed and eroded the entire Bakhtyari Formation since
23 some time in the Pliocene, or at least its non-deposition. This seems unlikely, given
24 that the structure has only a few 10s of metres of elevation above the surrounding
25 alluvial plains. Modern drainage patterns and deposition make a similar point:
26 drainage across the Dezful Embayment is centripetal, rising on all three mountainous
27 margins and focussing on the Tigris in the southwest. Rivers at the margins of the
28 Embayment are commonly braided and carry a cobble-grade bedload. Their
29 downstream equivalents in the Embayment interior are typically meandering (such as
30 the Dez and Karun, Figure 8) and carry more fine-grained sediment. These two
31 present settings probably typify much of the Late Cenozoic clastic sedimentation
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 across the Zagros, with the finer-grained, “Agha Jari” type passing upwards into
4
5 coarser “Bakhtyari” sediments as deformation advanced towards a given area, thereby
6
7 increasing relief and sediment grade. A further implication is that interpretations of
8
9 pulses of deformation, based on unconformities beneath conglomeratic facies (e.g.
10
11 Falcon, 1974), need to be treated with caution. Such a sedimentary switch might
12
13 represent the local progradation of higher energy transverse deposits over lower
14
15 energy axial or centripetal systems, not a Zagros-wide pulse of deformation.
16
17
18
19
20
21

22 Individual folds interact with drainage systems, typified by the Sardarabad
23
24 Anticline (Figure 8). This is a composite structure with four separate culminations
25
26 along its length (Llewellyn, 1972). The topographic relief above surrounding plains is
27
28 ~40 m. The Dez River is antecedent and cuts through the middle of the anticline.
29
30 Notably this is not at one of the relay zones between the culminations, but in the
31
32 middle of a culmination, at least at the present exposure level, which is mapped as the
33
34 Agha Jari Formation. The river changes planform from meandering to a relatively
35
36 straight reach as it crosses the fold, reverting to a meandering planform downstream,
37
38 which is a typical response of low gradient rivers as they cross a zone of active
39
40 surface uplift (Holbrook & Schumm, 1999). In contrast, the Karun River is diverted
41
42 around the southeast tip of the fold, presumably tracking the lateral growth of the fold
43
44 tip in the same direction.
45
46
47
48
49
50
51
52

53 Lateral fold growth is preserved in higher relief anticlines at the margins of the
54
55 Dezful Embayment, where wind gaps/dry valleys are preserved along fold crests, e.g.
56
57 near the eastern tip of the Kuh-e Chenareh anticline (Figures 3 and 9). Such wind gaps
58
59 are common in the Zagros (Burberry et al., 2008; Ramsey et al., 2008), and are useful
60

1
2
3 indicators of the previous patterns of drainage. The example in Figure 9 has relief of
4
5 125 m along the longitudinal wind gap profile, i.e. along the inferred original path of
6
7 the river channel from the upstream end (north) to the axis of the anticline. The
8
9 present drainage is diverted around the fold, lying some 3 km further east, but this
10
11 channel also lies within the topographic expression of the fold and so may in turn
12
13 become abandoned at some stage in the future. The rates of surface uplift and lateral
14
15 fold propagation are unknown.
16
17
18
19

20 21 22 **5. Discussion and conclusions**

23
24 The greater part of the Zagros lies within the **Simply Folded Belt**, but this region is
25
26 not homogeneous along strike, being an alternating sequence of low relief, low
27
28 elevation “embayments” and high relief, high elevation “salients” or “arcs” (Figure
29
30 1). These quotation marks are advisable: the deformation front is distinctly linear
31
32 along the Zagros west of the Kazerun Line, while the Fars region has an arcuate
33
34 deformation front that does not step abruptly southwards of the eastern limit of the
35
36 Dezful Embayment.
37
38
39
40
41
42

43
44 Published isopach data (Figure 4) show major differences in thicknesses or
45
46 facies between the Dezful Embayment and adjacent areas before the Late Cretaceous
47
48 (Koop & Stoneley, 1982; Motiei, 1993). Upper Cretaceous isopachs are thinner within
49
50 the Embayment than outside it, from which we infer that the Embayment first became
51
52 a distinct area at this time, but as a structural high (there is no evidence for local post
53
54 Late Cretaceous deformation, uplift and erosion removing strata across the
55
56 Embayment). This timing predates continental collision, but is consistent with the age
57
58 of ophiolite emplacement over the Arabian margin. The present distribution of
59
60

1
2
3 ophiolites has a notable correlation with the structure and stratigraphy of the
4
5 remainder of the Zagros to the southwest (Figure 1). Upper Cretaceous isopachs are
6
7 thicker in front of the Kermanshah and Neyriz ophiolites than the intervening region
8
9 (Dezful Embayment). We suggest that this stratigraphic variation results from
10
11 different nappe loading along the Arabian margin, i.e. the present distribution of the
12
13 ophiolites and Radiolarite Series reflects their original extent and is not simply an
14
15 artefact of differential erosion in the Cenozoic. It is less clear why ophiolite obduction
16
17 should have been irregular, and whether this was a consequence of the structure of the
18
19 Arabian margin (e.g. a promontory northeast of the present Dezful Embayment), or
20
21 lateral variation within the Tethyan oceanic crust and its subduction zone.
22
23
24
25
26
27
28

29
30 Paleogene isopachs and facies are little different between the Embayment and
31
32 its surroundings, consistent with this being a relatively quiescent time between the
33
34 ophiolite emplacement and the initial continental collision in the Late Eocene (Allen
35
36 & Armstrong, 2008). The Ahwaz Sandstone Member suggests clastic sediment was
37
38 preferentially transported in to the Embayment as far back as the Oligocene. The
39
40 Dezful Embayment is a Late Cenozoic depocentre, consistent with rapid subsidence in
41
42 this interval and in contrast to the elevation of neighbouring regions.
43
44
45
46
47

48
49 Variations along strike in the High Zagros occur at the same places as within
50
51 the **Simply Folded Belt**, and the intense imbrication of the Bakhtyari Culmination is
52
53 not matched by similar thrusting of Arabian plate margin in regions to the northwest
54
55 or southeast. This variation is consistent with an original promontory at this part of
56
57 the Arabian plate margin, now smoothed out by the collision. We further suggest that
58
59
60

1
2
3 this imbrication and thrust sheet loading resulted in greater subsidence of the Dezful
4
5 Embayment than other areas of the **Simply Folded Belt**.
6
7
8
9

10 **Acknowledgements.** We thank the Geological Survey of Iran for their help, without
11 which this work would have been impossible. Eric Blanc and James Jackson are
12 thanked for numerous discussions of Zagros geology. MBA acknowledges the
13 sponsors of CASP's Iran project. **Two anonymous referees provided very helpful and**
14 **constructive reviews, while the editorial efforts of Olivier Lacombe and Guy Simpson**
15 **are much appreciated.**
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

References

- ADAMS, A., BRAZIER, R., NYBLADE, A., RODGERS, A. & AL-AMRI, A. 2009. Source parameters for moderate earthquakes in the Zagros mountains with implications for the depth extent of seismicity. *Bulletin of the Seismological Society of America* 99, 2044-49.
- AGARD, P., OMRANI, J., JOLIVET, L. & MOUTHEREAU, F. 2005. Convergence history across Zagros (Iran): constraints from collisional and earlier deformation. *International Journal of Earth Sciences* 94, 401-19.
- AHMADHADI, F., LACOMBE, O. & DANIEL, J.M. 2007. Early reactivation of basement faults in Central Zagros (SW Iran): evidence from pre-folding fracture populations in the Asmari Formation and Lower Tertiary paleogeography. In *Thrust belts and foreland basins; from fold kinematics to hydrocarbon systems*, (eds. O. Lacombe, J. Lavé, J. Vergès & F. Roure), Springer Verlag, 205-228.
- ALAVI, M. 1994. Tectonics of the Zagros orogenic belt of Iran: new data and interpretations. *Tectonophysics* 239, 211-38.
- ALLEN, M. B. & ARMSTRONG, H. A. 2008. Arabia-Eurasia collision and the forcing of mid Cenozoic global cooling. *Palaeogeography Palaeoclimatology Palaeoecology* 265, 52-58.
- AMEEN, M. S. 1992. Effect of basement tectonics on hydrocarbon generation, migration and accumulation in northern Iraq. *Bulletin of the American Association of Petroleum Geologists* 76, 356-70.
- AUTHEMAYOU, C., CHARDON, D., BELLIER, O., MALEKZADEH, Z., SHABANIAN, E. & ABBASSI, M. R. 2006. Late Cenozoic partitioning of oblique plate convergence in the Zagros fold-and-thrust belt (Iran). *Tectonics* 25, Tc3002 doi: 10.1029/2005tc001860.

- 1
2
3 BABAIE, H. A., BABAEI, A., GHAZI, A. M. & ARVIN, M. 2006. Geochemical, Ar-
4 40/Ar-39 age, and isotopic data for crustal rocks of the Neyriz ophiolite, Iran.
5
6
7
8 *Canadian Journal of Earth Sciences* 43, 57-70.
- 9
10 BAHROUDI, A. & KOYI, H. A. 2003. Effect of spatial distribution of Hormuz salt on
11
12 deformation style in the Zagros fold and thrust belt: an analogue modelling approach.
13
14
15 *Journal of the Geological Society* 160, 719-33.
- 16
17 BAHROUDI, A. & KOYI, H. A. 2004. Tectono-sedimentary framework of the
18
19 Gachsaran Formation in the Zagros foreland basin, *Marine and Petroleum Geology*,
20
21 21, 1295-1310.
- 22
23 BAHROUDI, A. & TALBOT, C. J. 2003. The configuration of the basement beneath the
24
25 Zagros Basin. *Journal of Petroleum Geology* 26, 257-82.
- 26
27
28
29 BALLATO, P., UBA, C.E., LANDGRAF, A., STRECKER, M.R., MASAFUMI, S., STOCKLI,
30
31 D.F., FRIEDRICH, A. & TABATABAEI, S.H. in press. Arabia-Eurasia continental
32
33 collision: insights from late Tertiary foreland-basin evolution in the Alborz
34
35 mountains, northern Iran. *Bulletin of the Geological Society of America*.
- 36
37
38 BERBERIAN, M. 1995. Master "blind" thrust faults hidden under the Zagros folds:
39
40 active basement tectonics and surface morphotectonics. *Tectonophysics* 241, 193-224.
- 41
42
43 BEYDOUN, Z. R., HUGHES CLARKE, M. W. & STONELEY, R. 1992. Petroleum in the
44
45 Zagros Basin: a late Tertiary foreland basin overprinted onto the outer edge of a vast
46
47 hydrocarbon-rich Paleozoic-Mesozoic passive-margin shelf. In *Foreland Basins and*
48
49 *Foldbelts* (eds R. MacQueen and D. Leckie). pp. 309-39. AAPG Memoir 55.
- 50
51
52
53 BLANC, E. J.-P., ALLEN, M. B., INGER, S. & HASSANI, H. 2003. Structural styles in the
54
55 Zagros Simple Folded Zone, Iran. *Journal of the Geological Society, London* 160,
56
57 400-12.
58
59
60

1
2
3 BURBERRY, C. M., COSGROVE, J. W. & LIU, J. G. 2008. Spatial arrangement of fold
4 types in the Zagros Simply Folded Belt, Iran, indicated by landform morphology and
5 drainage pattern characteristics. *Journal of Maps*, 417-30.
6
7

8
9
10 CARRUBA, S., PEROTTI, C. R., BUONAGURO, R., CALABRO, R., CARPI, R. & NAINI, M.
11
12 2006. Structural pattern of the Zagros fold-and-thrust belt in the Dezful Embayment
13 (SW Iran). In *Styles of Continental Contraction* (eds S. Mazzoli & R. W. H. Butler).
14 pp. 11-32. Geological Society of America.
15
16
17

18
19
20 EDGELL, H. S. 1991. Proterozoic salt basins of the Persian Gulf area and their role in
21 hydrocarbon generation. *Precambrian Research* 54, 1-14.
22
23

24
25 CASCIELLO, E., VERGES, J., SAURA, E., CASINI, G., FERNANDEZ, N., BLANC, E.,
26
27 HOMKE, S. & HUNT, D. W. 2009. Fold patterns and multilayer rheology of the
28 Lurestan Province, Zagros Simply Folded Belt (Iran). *Journal of the Geological*
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

CAWOOD, P. A. & SUHR, G. 1992. Generation and obduction of ophiolites: Constraints
from the Bay of Islands Complex, Western Newfoundland. *Tectonics* 11, 884-97.

FAKHARI, M. D., AXEN, G. J., HORTON, B. K., HASSANZADEH, J. & AMINI, A. 2008.
Revised age of proximal deposits in the Zagros foreland basin and implications for
Cenozoic evolution of the High Zagros. *Tectonophysics* 451, 170-85.

FALCON, N. 1974. Southern Iran: Zagros mountains. In *Mesozoic-Cenozoic orogenic
belts: data for orogenic studies* (ed A. Spencer). pp. 199-211. Special Publication of
the Geological Society of London.

FARZIPOUR-SAEIN, A., YASSAGHI, A., SHERKATI, S. & KOYI, H. 2009. Mechanical
stratigraphy and folding style of the Lurestan region in the Zagros Fold-Thrust Belt,
Iran. *Journal of the Geological Society* 166, 1101-15.

- 1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
- GHAZI, A. M. & HASSANIPAK, A. A. 1999. Geochemistry of subalkaline and alkaline extrusives from the Kermanshah ophiolite, Zagros Suture Zone, Western Iran: Implications for Tethyan plate tectonics. *Journal of Asian Earth Sciences* 17, 319-32.
- GOK, R., MAHDI, H., AL-SHUKRI, H. & RODGERS, A. J. 2008. Crustal structure of Iraq from receiver functions and surface wave dispersion: implications for understanding the deformation history of the Arabian-Eurasian collision. *Geophysical Journal International* 172, 1179-87.
- GUEST, B., STOCKLI, D.F., GROVE, M., AXEN, G.J., LAM, P.S. & HASSANZADEH, J. 2006. Thermal histories from the central Alborz Mountains, northern Iran: Implications for the spatial and temporal distribution of deformation in northern Iran, *Geological Society of America Bulletin* 118, 1507-1521.
- HESSAMI, K., KOYI, H. A. & TALBOT, C. J. 2001. The significance of strike-slip faulting in the basement of the Zagros fold and thrust belt. *Journal of Petroleum Geology* 24, 5-28.
- HESSAMI, K., NILFOROUSHAN, F. & TALBOT, C. J. 2006. Active deformation within the Zagros Mountains deduced from GPS measurements. *Journal of the Geological Society* 163, 143-48.
- HOLBROOK, J. & SCHUMM, S. A. 1999. Geomorphic and sedimentary response of rivers to tectonic deformation: a brief review and critique of a tool for recognizing subtle epeirogenic deformation in modern and ancient settings. *Tectonophysics* 305, 287-306.
- HOMKE, S., VERGÉS, J., GARCÉS, M., EMAMI, H. & KARPUZ, R. 2004. Magnetostratigraphy of Miocene–Pliocene Zagros foreland deposits in the front of the Push-e Kush Arc (Lurestan Province, Iran). *Earth and Planetary Science Letters* 225, 397-410.

1
2
3 HOMKE, S., VERGES, J., SERRA-KIEL, J., BERNAOLA, G., SHARP, I., GARCES, M.,
4
5 MONTERO-VERDU, I., KARPUZ, R. & GOODARZI, M. H. 2009. Late Cretaceous-
6
7 Paleocene formation of the proto-Zagros foreland basin, Lurestan Province, SW Iran.
8
9

10 *Geological Society of America Bulletin* 121, 963-78.

11
12 JACKSON, J. A. 1980. Reactivation of basement faults and crustal shortening in
13
14 orogenic belts. *Nature* 283, 343-46.

15
16
17 JAMES, G. A. & WYND, J. G. 1965. Stratigraphic nomenclature of the Iranian oil
18
19 consortium agreement area. *Bulletin of the American Association of Petroleum*
20
21 *Geologists* 49, 2182-245.

22
23
24 JARVIS A., REUTER, H.I., NELSON, A. & GUEVARA, E. 2008. Hole-filled seamless
25
26 SRTM data V4, International Centre for Tropical Agriculture (CIAT), available from
27
28 <http://srtm.csi.cgiar.org>.

29
30
31 KENT, P. E. 1979. The emergent Hormuz salt plugs of southern Iran. *Journal of*
32
33 *Petroleum Geology* 2, 117-44.

34
35
36 KOOP, W. J. & STONELEY, R. 1982. Subsidence history of the Middle East Zagros
37
38 Basin, Permian to Recent. *Philosophical Transactions of Royal Society of London*
39
40 A305, 149-68.

41
42
43 LLEWELLYN, P. 1972. Ahwaz. Tehran: Iranian Oil Operating Companies.

44
45 LLEWELLYN, P. 1973. Dezful. Tehran: Iranian Oil Operating Companies.

46
47
48 MAGGI, A., JACKSON, J. A., PRIESTLEY, K. & BAKER, C. 2000. A re-assessment of
49
50 focal depth distributions in southern Iran, the Tien Shan and northern India: do
51
52 earthquakes really occur in the continental mantle? *Geophysical Journal International*
53
54 143, 629-61.

55
56
57 MCQUARRIE, N. 2004. Crustal scale geometry of the Zagros fold-thrust belt, Iran.
58
59
60 *Journal of Structural Geology* 26, 519-35.

1
2
3 MOHAJJEL, M., FERGUSSON, C. L. & SAHANDI, M. R. 2003. Cretaceous-Tertiary
4 convergence and continental collision, Sanandaj-Sirjan Zone, western Iran. *Journal of*
5
6 *Asian Earth Sciences* 21, 397-412.
7

8
9
10 MOLINARO, M., ZEYEN, H. & LAURENCIN, X. 2005. Lithospheric structure beneath the
11
12 south-eastern Zagros Mountains, Iran: recent slab break-off? *Terra Nova* 17, 1-6.
13

14
15 MORRIS, P. 1977. Basement structure as suggested by aeromagnetic survey in SW
16
17 Iran. Internal Report, Oil Service Company of Iran.
18

19
20 MOTIEI, H. 1993. *Stratigraphy of Zagros*. Tehran: Geological Survey of Iran.
21

22
23 MOUTHEREAU, F., LACOMBE, O. & MEYER, B. 2006. The Zagros folded belt (Fars,
24
25 Iran): constraints from topography and critical wedge modelling. *Geophysical Journal*
26
27 *International* 165, 336-56.
28

29
30 MOUTHEREAU, F., TENSI, J., BELLAHSEN, N., LACOMBE, O., DE BOISGROLLIER, T. &
31
32 KARGAR, S. 2007. Tertiary sequence of deformation in a thin-skinned/thick-skinned
33
34 collision belt: The Zagros folded belt (Fars, Iran). *Tectonics* 26, art. no. Tc5006 doi:
35
36 10.1029/2007tc002098.
37

38
39 MURRIS, R. J. 1980. Middle East: Stratigraphic evolution and oil habitat. *American*
40
41 *Association of Petroleum Geologists Bulletin* 64, 597-618.
42

43
44 NATIONAL IRANIAN OIL COMPANY 1975. Geological Map of Iran Sheet 4 South-West
45
46 Iran. Tehran: National Iranian Oil Company.
47

48
49 NATIONAL IRANIAN OIL COMPANY 1977a. Geological Map of Iran Sheet 5 South-
50
51 Central Iran. Tehran: National Iranian Oil Company.
52

53
54 NATIONAL IRANIAN OIL COMPANY 1977b. Geological Map of Iran Sheet 6 South-East
55
56 Iran. Tehran: National Iranian Oil Company.
57

58
59 NATIONAL IRANIAN OIL COMPANY 1978. Geological Map of Iran Sheet 1 North-West
60
Iran. Tehran: National Iranian Oil Company.

1
2
3 O'BRIEN, C.A.E. 1957. Salt diapirism in South Persia. *Geologie en Mjinbouw* 19, 357-
4
5
6 376.

7
8 OKAY, A. I., ZATTIN, M. & CAVAZZA, W. 2010. Apatite fission-track data for the
9
10 Miocene Arabia-Eurasia collision. *Geology* 38, 35-38.

11
12 PAUL, A., HATZFELD, D., KAVIANI, A., TATAR, M. & PÉQUEGNAT, C. 2010. Seismic
13
14 imaging of the lithospheric structure of the Zagros mountain belt (Iran). In *Tectonic*
15
16 *and Stratigraphic Evolution of Zagros and Makran during the Mesozoic–Cenozoic*
17
18 eds P. Leturmy and C. Robin. pp. 5-18. Geological Society, London, Special
19
20 Publications 330.

21
22
23
24 RAMSEY, L. A., WALKER, R. T. & JACKSON, J. 2008. Fold evolution and drainage
25
26 development in the Zagros mountains of Fars province, SE Iran. *Basin Research* 20,
27
28 23-48.

29
30
31 SELLA, G. F., DIXON, T. H. & MAO, A. 2002. REVEL: A model for recent plate
32
33 velocities from space geodesy. *Journal of Geophysical Research* 107, art. no. 2081
34
35 doi 10.1029/2000JB000033.

36
37
38 SENGÖR, A. M. C., ALTINER, D., CIN, A., USTAOMER, T. & HSU, K. J. 1988. Origin
39
40 and assembly of the Tethyside orogenic collage at the expense of Gondwana Land.
41
42 eds M. G. Audley-Charles and A. Hallam. pp. 119-81. Geological Society, London,
43
44 Special Publications 37.

45
46
47 SEPEHR, M. & COSGROVE, J. W. 2004. Structural framework of the Zagros Fold-
48
49 Thrust Belt, Iran. *Marine and Petroleum Geology* 21, 829-43.

50
51
52 SEPEHR, M. & COSGROVE, J. W. 2005. Role of the Kazerun Fault Zone in the
53
54 formation and deformation of the Zagros Fold-Thrust Belt, Iran. *Tectonics*, 24,
55
56 Tc5005, doi:10.1029/2004tc001725.
57
58
59
60

1
2
3 SETUDEHNI, A. 1978. The Mesozoic sequence in south-west Iran and adjacent areas.

4
5
6 *Journal of Petroleum Geology* 1, 3-42.

7
8 SHARLAND, P. R., ARCHER, R., CASEY, D. M., DAVIES, R. B., HALL, S. H., HEWARD,

9
10 A. P., HORBURY, A. D. & SIMMONS, M. D. 2001. *Arabian plate sequence stratigraphy*.

11
12 Manama, Bahrain: GeoArabia.

13
14 SHERKATI, S. & LETOUZEY, J. 2004. Variation of structural style and basin evolution

15
16 in the central Zagros (Izeh zone and Dezful Embayment), Iran. *Marine and Petroleum*

17
18 *Geology* 21, 535-54.

19
20 SHERKATI, S., MOLINARO, M., DE LAMOTTE, D. F. & LETOUZEY, J. 2005. Detachment

21
22 folding in the Central and Eastern Zagros fold-belt (Iran): salt mobility, multiple

23
24 detachments and late basement control. *Journal of Structural Geology* 27, 1680-96.

25
26 SZABO, F. & KHERADPIR, A. 1978. Permian and Triassic stratigraphy, Zagros Basin,

27
28 south-west Iran. *Journal of Petroleum Geology* 1, 57-82.

29
30 Talbot & Alavi 1996.

31
32 TALEBIAN, M. & JACKSON, J. 2002. Offset on the Main Recent Fault of NW Iran and

33
34 implications for the late Cenozoic tectonics of the Arabia-Eurasia collision zone.

35
36 *Geophysical Journal International* 150, 422-39.

37
38 TALEBIAN, M. & JACKSON, J. 2004. A reappraisal of earthquake focal mechanisms

39
40 and active shortening in the Zagros mountains of Iran. *Geophysical Journal*

41
42 *International* 156, 506-26.

43
44 TATAR, M., HATZFELD, D. & GHAFORY-ASHTIANY, M. 2004. Tectonics of the Central

45
46 Zagros (Iran) deduced from microearthquake seismicity. *Geophysical Journal*

47
48 *International* 156, 255-266.

49
50 VERNANT, P., NILFOROUSHAN, F., HATZFELD, D., ABBASSI, M., VIGNY, C., MASSON,

51
52 F., NANKALI, H., MARTINOD, J., ASHTIANI, A., BAYER, R., TAVAKOLI, F. & CHERY, J.

53
54
55
56
57
58
59
60

1
2
3 2004. Contemporary crustal deformation and plate kinematics in Middle East
4
5 constrained by GPS measurements in Iran and northern Iran. *Geophysical Journal*
6
7 *International* 157, 381-98.
8
9

10 VINCENT, S.J., ALLEN, M.B., ISMAIL-ZADEH, A.D., FLECKER, R., FOLAND, K.A. &
11
12 SIMMONS, M.D. 2005. Insights from the Talysh of Azerbaijan into the Paleogene
13
14 evolution of the South Caspian region. *Bulletin of the Geological Society of America*
15
16 117, 1513-1533.
17
18

19 WALPERSDORF, A., HATZFELD, D., NANKALI, H., TAVAKOLI, F., NILFOROUSHAN, F.,
20
21 TATAR, M., VERNANT, P., CHERY, J. & MASSON, F. 2006. Difference in the GPS
22
23 deformation pattern of north and central zagros (Iran). *Geophysical Journal*
24
25 *International* 167, 1077-88.
26
27

28
29 YOUSEFI, E. & FRIEDBERG, J. L. 1978. Aeromagnetic map of Iran. Tehran: Geological
30
31 Survey of Iran.
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Figure captions

Figure 1. (a). Location map and major structures of the Zagros Simply Folded Belt, Iran. Derived from National Iranian Oil Company (1975b; 1977a; 1977b), Berberian (1995), Hessami et al. (2001), Blanc et al (2003), Agard et al. (2005) and Babaie et al. (2006). Key to fault abbreviations: B = Borazjan; Iz = Izeh; K = Kazerun; KB = Karez Bas; Kh = Khanaqin; S = Sarvestan; SP = Sabz Pushan. BL is the Balarud Line; A is Kuh-e Asmari. (b) Location map for Figure 1a. CIM = Central Iranian Microcontinent.

Figure 2. Stratigraphy of the Iranian Zagros. Modified from Iran Oil Operating Companies (1969), to reflect the diachronous nature of the Bakhtyari Formation (Fakhari *et al.* 2008).

Figure 3. Dezful Embayment structural map, overlain on Shuttle Radar Topography Mission (SRTM) digital topography (using the CGIAR datasets, Jarvis *et al.* 2008). Black focal mechanisms: Body wave modelled focal mechanisms and fault plane solutions from Talebian & Jackson (2004) and references therein. Grey focal mechanisms: Harvard CMT events from 1977 to 2008 with >70% double-couple. Centroid depths (km) are shown in italics. Anticlines are highlighted west of the Dezful Embayment Fault.

Figure 4. Isopachs of selected intervals for the Dezful Embayment and adjacent areas. Derived from Koop & Stoneley (1982) and Motiei (1993).

1
2
3 Figure 5. Structural cross-section for the Dezful Embayment. Constructed from data
4 in Llewellyn (1972, 1973) and NIOC (1975), with input from our fieldwork
5 observations, seismicity (Figure 3), published isopach maps and the half graben
6 geometry shown by Sepehr & Cosgrove (2004). **The dashed line near the base of the**
7 **sedimentary succession represents a speculative detachment at the level of the**
8 **Hormuz Series salt or an equivalent.** Location shown on Figure 3.
9
10
11
12
13
14
15
16
17
18
19

20 Figure 6. Field photographs of structures at the margins of the Dezful Embayment. (a)
21 Kuh-e Kamar Meh and the position of the Mountain Front Fault (arrowed); (b)
22 termination of the Kabir Kuh anticline, where Asmari Limestone strata (AS) plunge
23 south towards the Balarud Line, with low relief Gachsran Formation evaporites (GF)
24 in the foreground; (c) View across the Balarud Line (arrowed) to the Kuh-e Chenareh
25 anticline; (d) juxtaposition of the Gachsaran Formation (GF) and Quaternary
26 sediments (Q) across the Dezful Embayment Fault at Haft Kel.
27
28
29
30
31
32
33
34
35
36
37
38

39 Figure 7. Landsat TM imagery of the Balarud Line, at the northern side of the Dezful
40 Embayment, **draped over SRTM topography**. This shows that no clear-cut fault can be
41 seen at the surface in this area. Anticlines approach the Balarud Line from both the
42 northwest and southeast, and are deflected towards more east-west orientations, but
43 there is no bedrock, geomorphic or seismicity evidence for left-lateral faulting along
44 the Line.
45
46
47
48
49
50
51
52
53
54

55 Figure 8. Landsat TM image of the Sardarabad anticline in the Dezful Embayment, at
56 50% transparency and draped over SRTM digital topography (scale saturated at 100
57 m elevation), illustrating the low relief of active structures within the Embayment
58
59
60

1
2
3 area. Whilst the Dez River has enough stream power to cut through the rising fold, the
4
5 Karun River is deflected to the east around the fold tip. Double-headed arrows mark
6
7 the individual anticline axes mapped by Llewellyn (1972). **The topographic profile X-**
8
9 **X' has ~75x vertical exaggeration, and illustrates the low relief of anticlines within**
10
11 **the Dezful Embayment.**
12
13
14
15
16

17 Figure 9. Wind gap development at Kuh-e Chenareh. (a) **Landsat image draped over**
18
19 **SRTM topography of the Kuh-e Chenareh anticline, showing the topographic plunge**
20
21 **towards the ESE; (b) view northwards from the crest of the wind gap (“eye” symbol**
22
23 **in (a)), showing the gorge created by the original drainage through the Asmari**
24
25 **Limestone bedrock; (c) topographic profile along X-X' in (a), showing the present**
26
27 **relief along the original north-to-south river channel.**
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

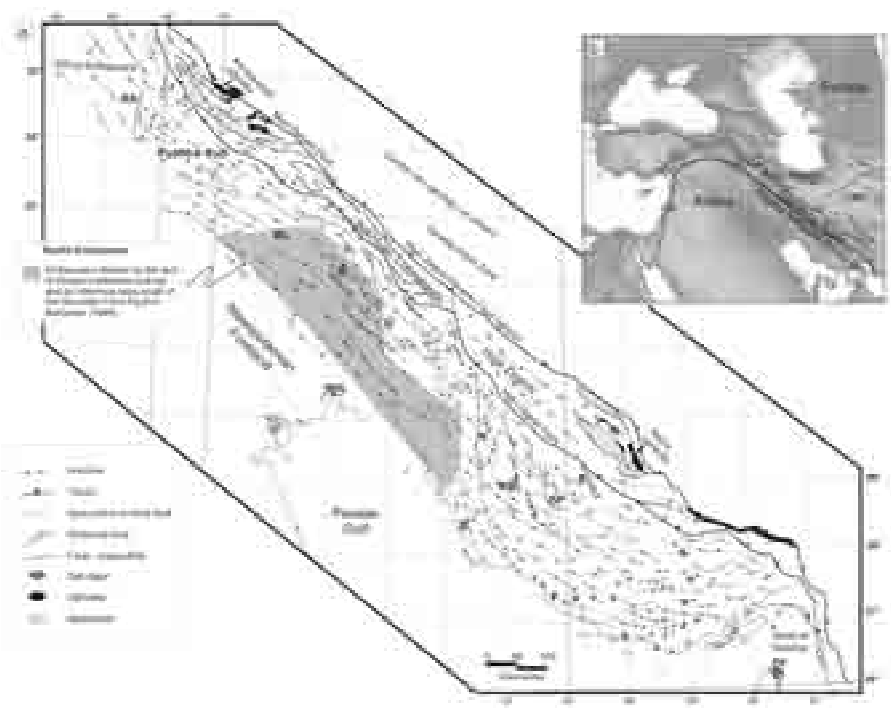


Figure 1
279x196mm (600 x 600 DPI)

Review

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

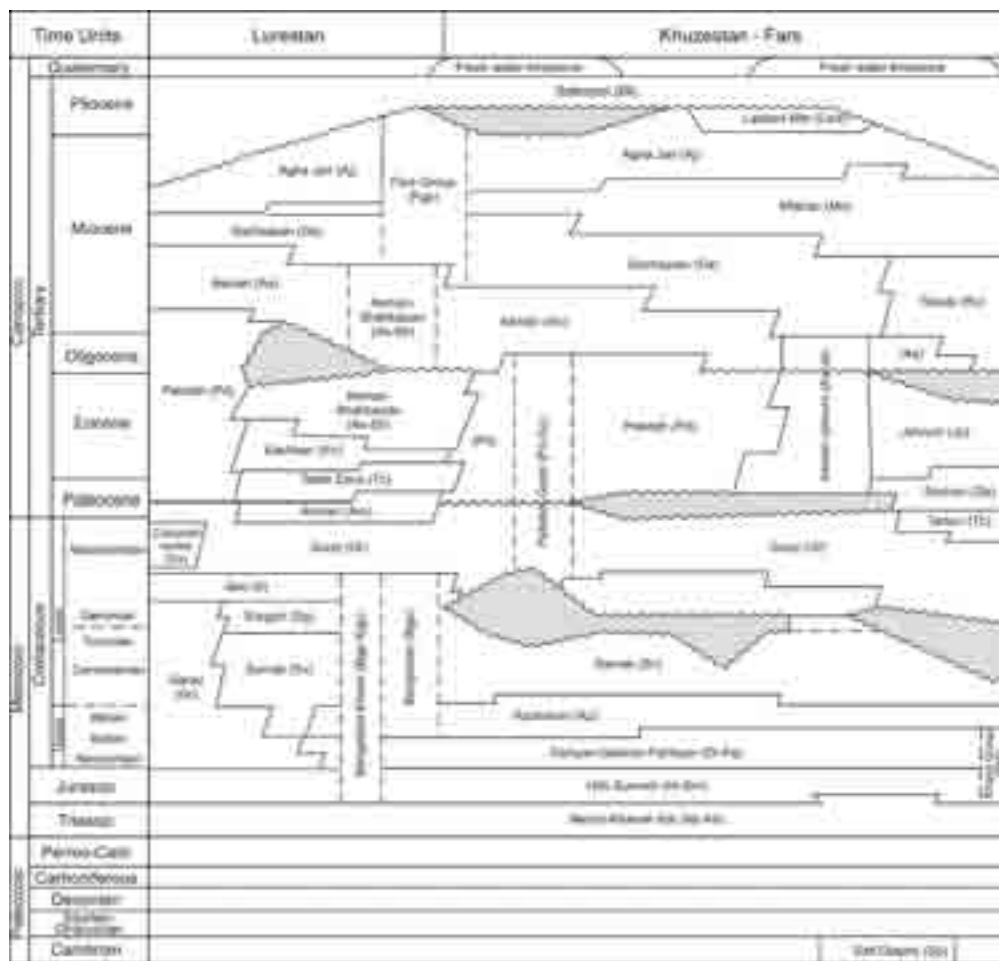


Figure 2
151x143mm (600 x 600 DPI)



1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

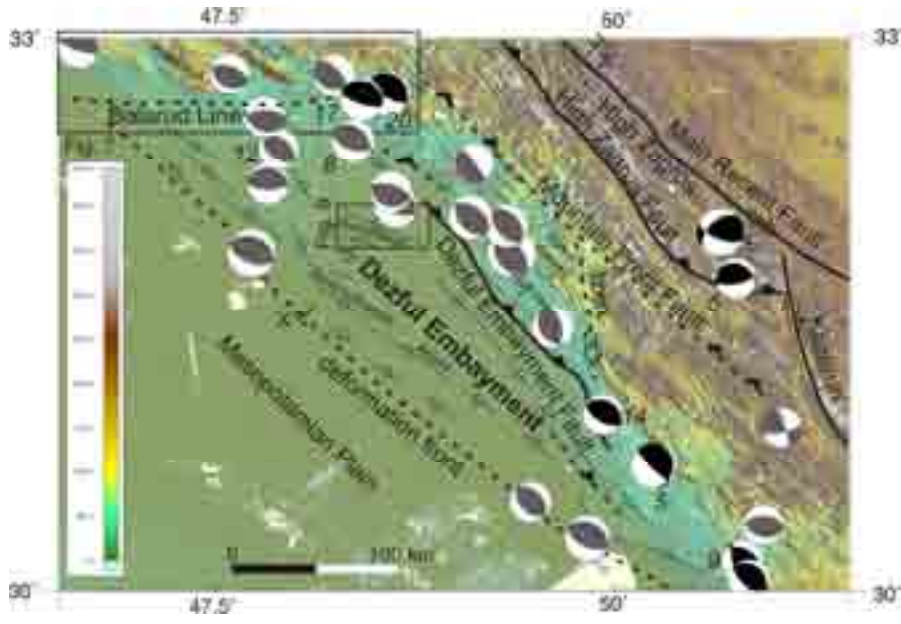


Figure 3
208x126mm (300 x 300 DPI)

For Review

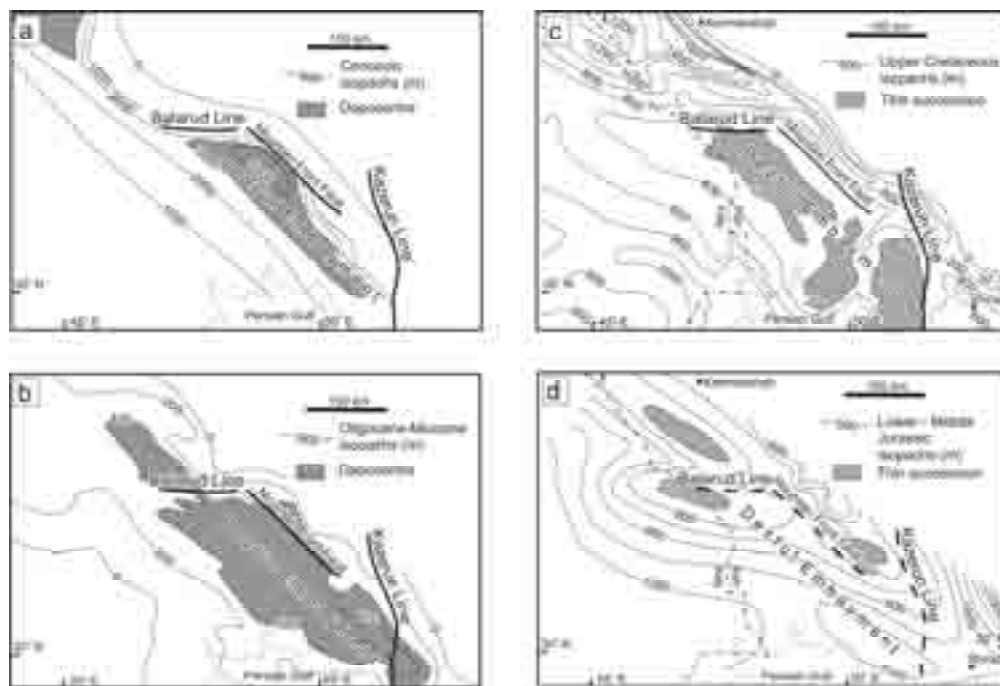


Figure 4
257x174mm (600 x 600 DPI)

Review

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

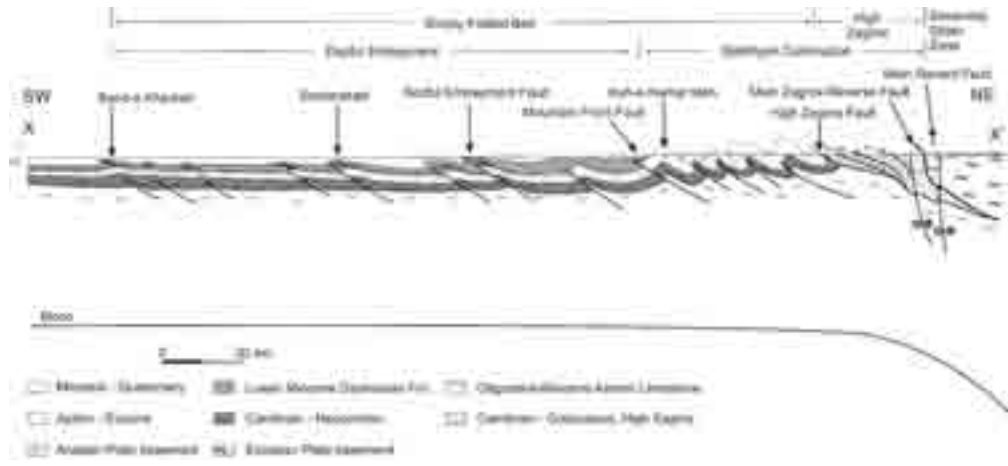


Figure 5
242x109mm (600 x 600 DPI)

For Review

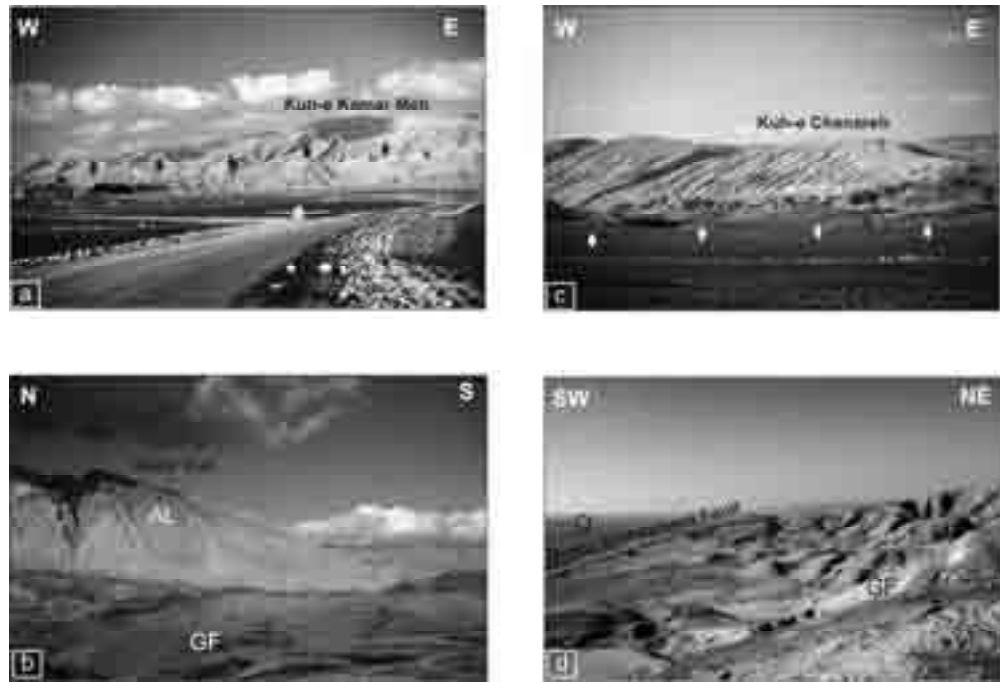


Figure 6
185x125mm (600 x 600 DPI)

Review

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60



Figure 7
175x66mm (300 x 300 DPI)

Proof For Review

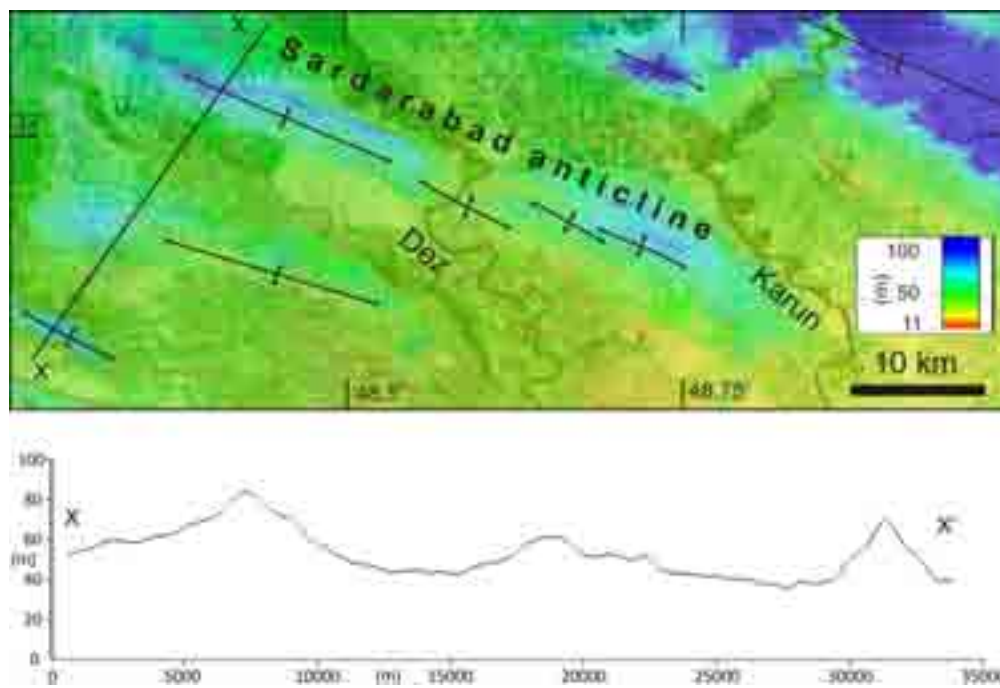


Figure 8
157x106mm (300 x 300 DPI)

Review

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

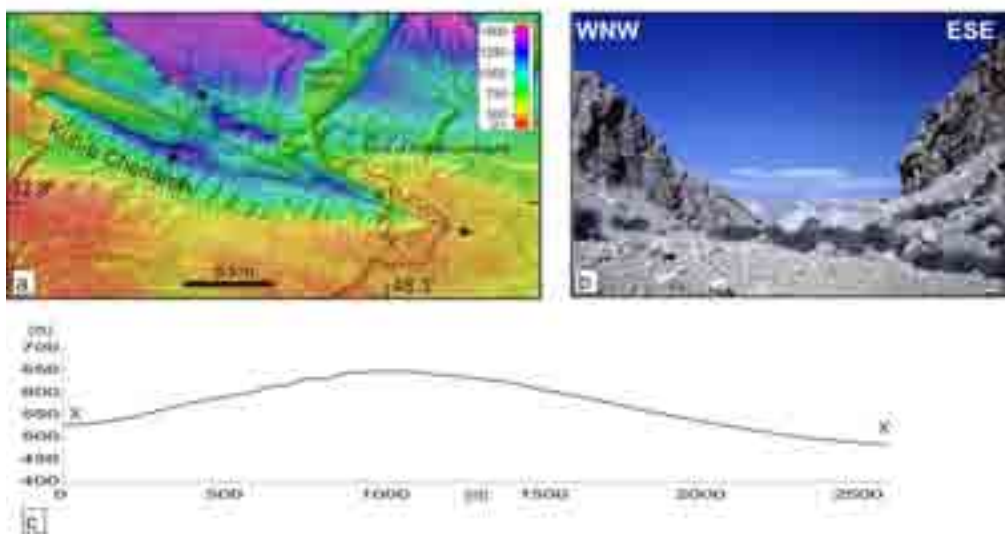


Figure 9
175x103mm (300 x 300 DPI)

or Review