Fold patterns and multilayer rheology of the Lurestan Province, Zagros Simply Folded Belt (Iran)

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Abstract: Anticlines of the Lurestan Province in the Zagros fold–thrust belt have been studied by integrating field-based analysis with the use of high-resolution satellite images and data available from the literature. The distribution of folds in the southeastern Lurestan Province, expressed in terms of axial length and wavelength, shows a direct link with the characteristics of the sedimentary multilayer in which the folds developed. Within the carbonate deposits of the Late Cretaceous Bangestan Group the transition from pelagic to nectonic facies determines a threefold increase in anticline spacing and promotes the development of thrust structures in the forelimb of anticlines. The Oligocene–Miocene Shahbazan–Asmari unit folds harmonically with the Bangestan Group, except in the areas where the Palaeogene deposits interposed between the two units exceed 1300 m of thickness. In these areas the Shahbazan–Asmari carbonates display short-wavelength folds indicating a complete decoupling from the underlying folds of the Bangestan Group. It is suggested that this decoupling occurs because the summed thickness of the incompetent units separating the two carbonate units exceeds the extension of the zone of effective contact strain of the Bangestan Group folds.

The Zagros mountain range is a NW–SE-trending segment of the Alpine–Himalayan collisional belt originating from the Late Cretaceous–Cenozoic convergence of the Arabian and the Eurasian plates (Talbot & Alavi 1996; Stampfl & Borel 2002; Golonka 2004). The Zagros have been traditionally subdivided into structural zones trending parallel to the plate suture, which are characterized by distinctive lithologies and structural styles, and are separated by regional-scale faults such as the Main Zagros Thrust, the High Zagros Fault and the Mountain Front Fault (Fig. 1; Falcon 1969; Berberian 1995). The Simply Folded Belt presents spectacular trains of folds developed in a thick multilayer of Palaeozoic to Cenozoic sediments that accumulated on the northern margin of the Arabian plate. It is bounded to the NE by the High Zagros Fault, separating it from the Imbricate Zone, and to the SW it is delimited by the Mountain Front Fault. This latter structure is a regional morphotectonic feature, delineated by a clustering of seismic events (Berberian 1995; Jackson & McKenzie 1984; Engdahl et al. 2006), which produces a sudden change in the lithology of the exposed multilayer (Falcon 1961). The sinuous trace of the Mountain Front Fault defines two arcs, the Fars Arc to the SE and the Push–e Kuh (Lurestan) Arc to the NW, separated by a re-entrant area known as the Dezful Embayment (Fig. 1). Both the Simply Folded Belt and the Dezful Embayment contain many large oil and gas fields, hosted in the broad and large-amplitude anticlines that characterize these regions.

The folds of the Fars Arc were originally interpreted as buckle folds, characterized by the periclinal (whaleback) geometry and en-echelon distribution (Colman-Sadd 1978; Sattarzadeh et al. 2000). However, further studies conducted in the Fars region and in the central Zagros (Molinaro et al. 2005; Sherkati et al. 2005; Carruba et al. 2006; Sepehr et al. 2006) have indicated that more than one mechanism is responsible for the growth of folds in the Simply Folded Belt, and that their geometry, size and distribution is intimately related to the mechanical properties of the folding multilayer (Sherkati & Letouzey 2004; Sepehr et al. 2006). The present study analyses for the first time the characteristics and the distribution of folds in the southeastern Push–e Kuh Arc, with the intent of gaining some insights into the mechanical behaviour of the sedimentary cover in this portion of the Zagros. To this end, anticlines have been analysed in terms of persistence and spacing, which are then compared with stratigraphic parameters such as the thickness and facies distribution of the folding units to highlight the controlling factors that govern folding in this area.

Geological framework and stratigraphy of the Lurestan Province

The spectacular folds of the Simply Folded Belt formed in a thick sedimentary succession that ranges in age from the Late Proterozoic to Pleistocene and measures c. 10–13 km in thickness (Colman-Sadd 1978; Alavi 2004; Farzipur-Saein et al. 2008). In the Fars Province the base of this stratigraphic pile is formed by a thick Infracambrian evaporite unit (Hormuz Formation), which directly overlies the metamorphic basement and acts as an extremely efficient detachment horizon (O’Brien 1950; Colman-Sadd 1978). The presence of the Hormuz Formation, which is too deep to be drilled, is documented by over 100 salt plugs that pierced the whole sedimentary cover of the Fars Arc and are exposed at surface. Conversely, the absence of salt plugs in the remaining northern regions has been interpreted as evidence for the lack of the Infracambrian Hormuz evaporite at the base of the sedimentary cover (Bahroudi & Koyi 2003; 2006).
However, based on the shape of the folds and the very low taper angle of the chain several researchers have challenged this hypothesis, suggesting that in the Dezful, Izeh and Lurestan regions the Hormuz Formation may either be thinner than the 1–2.5 km estimated for the Fars region (Ala 1974; Edgell 1996) or may be replaced by an equally efficient detachment horizon (McQuarrie 2004; Sherkati & Letouzey 2004; Carruba et al. 2006). Above the presumed Hormuz Formation of the Lurestan region, the Palaeozoic succession is formed by Cambro-Ordovician epicontinental deposits, mainly clastic (shales and sandstones) with minor carbonates and evaporites, which are unconformably overlain by Permian units (Fig. 2; Setudenhia 1975; Berberian & King 1981; Koop & Stoneley 1982; Ghavidel-syooki 2008). During Late Permian–Triassic times, NE–SW extension related to the opening of the Neotethys Ocean generated a stable and subsiding passive margin on the northeastern side of the Arabian plate, which persisted throughout the Mesozoic (Stöcklin 1968; Berberian & King 1981; Husseini 1988). A remarkable feature of the Mesozoic stratigraphic evolution is the differentiation of the Lurestan and the Fars regions as distinct depositional domains. Whereas the Fars region recorded neritic conditions throughout the Jurassic and Early Cretaceous (Surmeh, Fahliyan formations) the Lurestan region remained a silled area in which shales, pelagic limestones and evaporites were alternatively deposited (Fig. 3; James & Wynd 1965; Setudenhia 1978; Szabo & Kheradpir 1978; Koop & Stoneley 1982). From the early Aptian, however, neritic carbonate facies started prograding from the south across the Lurestan basin (Fig. 4) leading to the deposition of the late Albian–Turonian Sarvak Formation, which forms the lower oil reservoir in the Lurestan region, with an average thickness of 600–800 m (James & Wynd 1965; Setudenhia 1978). Towards the end of the Cretaceous the Neotethys started closing (Stöcklin 1968). Obduction of ophiolite and radiolarite units on the northeastern margin of the Arabian plate during the Campanian–Maastrichtian determined the end of passive margin conditions and the deposition of a shallowing upward clastic wedge formed by the Amiran, Taleh Zang and Kashkan Forma-
disconformably on the Shahbazan Formation; however, this unconformity is generally difficult to distinguish in the field and the two units are generally mapped as a single unit referred to as the Shahbazan–Asmari unit. These carbonate deposits form the upper reservoir unit in the Dezful embayment, where they are covered by c. 1 km of Early Miocene Gachsaran evaporites and 2.5 km of Late Miocene–Pliocene alluvial Agha Jari deposits (Homke et al. 2004; Carruba et al. 2006). Deformation of the thick sedimentary cover of the Zagros is thought to have occurred in two steps, an initial thin-skinned phase of folding, mainly above the Hormuz evaporite, followed by thick-skinned basement faulting that generates sudden variations in the level of exposure across the Simply Folded Belt (Blanc et al. 2003; Molinaro et al. 2005; Sherkati et al. 2005; Moutheureau et al. 2007). The Mountain Front Fault bounding the Push-te Kuh Arc (Fig. 1) is an expression of this late-stage basement faulting, and has produced a mean topographic uplift of 1000 m and a structural uplift in excess of 3 km (Emami et al. 2009). The trace of this blind tectonic element is composed of various seismic segments including an east–west segment, known as the Bala Rud fault zone, which runs obliquely to the NW–SE-trending folds of the Simply Folded Belt and defines the northern boundary of the Dezful embayment (Berberian 1995; Sepehr & Cosgrove 2004). Magnetostratigraphic studies along the frontal anticline of the Push-te Kuh Arc indicate that the deformation front reached this position during the Late Tortonian (7.6 ± 0.5 Ma), generating growth strata in the upper half of the fluvial Agha Jari Formation (Homke et al. 2004).

Mechanical stratigraphy of the Lurestan succession

The link between the style of deformation and the rheological profile of the sedimentary succession was initially established by O’Brien (1950), who subdivided the Zagros vertical profile into five structural units: the Basement group, the Lower Mobile group (Hormuz evaporite), the Competent group (Cambrian to Oligocene rocks), the Upper Mobile group (Gachsaran formation) and the Passive group (Agha Jari and Bakhtyari formations). Early structural interpretations of the Simply Folded Belt considered its large anticlines as buckle folds of the Competent group, formed by detachment above the Lower Mobile group, which generated relatively simple structures with wavelengths in excess of 10 km, reflecting the great thickness of the Competent unit (6–7 km) and the depth of the detachment horizon (Colman-Sadd 1978). In the upper part of the section, the high mobility of the Gachsaran evaporite allows the formation of folds in the overlying Passive group that are disharmonic with respect to the Competent Group folds (O’Brien 1950; Sherkati et al. 2005; Carruba et al. 2006). O’Brien’s schematic subdivision, with a thick Competent group, describes adequately the mechanical stratigraphy of the Fars region, where the Mesozoic units form an almost continuous succession of limestones and dolomites (Fig. 3). Detailed studies conducted in the Dezful and Izeh zones have documented, however, the existence of additional detachment horizons within the Competent Group, such as the Triassic Dashtak evaporites, the Lower Cretaceous Kazhdumi shales and the Upper Cretaceous Gurpi–Pabdeh marls (Sherkati et al. 2005; Carruba et al. 2006; Sepehr et al. 2006). In the Lurestan Province the stratigraphy of the sedimentary cover is rather different from that of the Fars region, particularly for the Jurassic and Early Cretaceous, when the area occupied at present by the Simply Folded Belt was characterized by pelagic thin-bedded limestones, shales and evaporites (Fig. 2; Setudehnia 1978; Koop & Stoneley 1982). In terms of mechanical stratigraphy these
deposits provide further potential detachment horizons (Alan, Gotnia and Garau formations) in addition to those recognized in adjoining areas (i.e. Dashtak and Gurpi–Pabdeh formations). Furthermore, the lack of the Surmeh, Falhliyan and Dariyan formations in a large part of the Lurestan region (Fig. 3) leads us to hypothesize that the role of ‘competent’ units in this region is played uniquely by the Bangestan Group (Sarvak and Ilam formations) and by the Shahbazan–Asmari carbonates, which also represent the two principal topography-forming units in this area. As one of the factors governing fold wavelength is the thickness of the buckling layer, the reduced thickness of the Competent group in the Lurestan area is thought to be the cause of the overall shorter wavelength of folds observable in this region of the Simply Folded Belt (Colmann-Sadd 1978; Blanc et al. 2003; Sepehr et al. 2006). Besides the differences in the Mesozoic stratigraphy, the Cenozoic units of the Lurestan sedimentary cover also differ from those of the rest of the Zagros. During the Palaeogene, in fact, the establishment of an early foreland–basin setting as a consequence of Late Cretaceous obduction of radiolarite and ophiolite tectonic slices (Ricou et al. 1977) led to the deposition of a thick clastic wedge interposed between the Bangestan Group and the Shahbazan–Asmari carbonates. As will be demonstrated below, the variations in thickness that characterize the Palaeogene foreland deposits can influence the style of folding of the overlying Shahbazan–Asmari unit.

**Distribution of folds in the Simply Folded Belt of the southeastern Lurestan Province**

The southeastern termination of the Pusht-e Kuh Arc (Fig. 1) was selected to analyse fold patterns along the Simply Folded Belt. This portion of the Simply Folded Belt is particularly interesting as it contains the transition between the Pusht-e Kuh Arc and the Bakhtyari culmination, accompanied by a rapid change in the level of exposure along the NW–SE trend of the folds (Fig. 5). The Bakhtyari culmination is the narrowest segment of the Simply Folded Belt, measuring only 50–60 km in width, and exposing the Jurassic and Cretaceous Khami and Bangestan Groups. In contrast, in the Pusht-e Kuh Arc, where the Simply Folded Belt reaches a width of c. 160 km, the units most frequently exposed at the surface are the Oligocene–Miocene Shahbazan–Asmari carbonates and the Gachsaran Formation. This variation in the level of exposure allows comparison, across a relatively short distance and along the strike of the folds, of the characteristics of deformation within the two superimposed carbonate units that form the upper and lower reservoir units throughout the Zagros range (Bordenave & Hegre 2005). The variation in width of the Simply Folded Belt is caused by the change in trend of the Mountain Front Fault, which passes from a NW–SE trend along the foothills of the Bakhtyari culmination to an east–west trend along the southern part of the Pusht-e Kuh Arc (Bala Rud fault zone). The obliquity of the
Fig. 5. Geological map of the southeastern portion of the Pusht-e Kuh Arc; slightly modified from NIOC geological maps (1:100,000 scale). Location is shown in Figure 1.

Fig. 6. Axial traces of anticlines in the study area. Fold traces were initially traced from NIOC geological maps (1:100,000 scale) and were successively integrated and modified using high-resolution 3D-stereo satellite images. Three domains, characterized by an approximately homogeneous spacing and axial length, are readily discernible.
Bala Rud trend with respect to the shortening direction indicated by folds has led to this blind fault zone being interpreted as a left lateral shear zone (Berberian 1995; Sepehr & Cosgrove 2004). However, it is worth noting that published focal mechanisms document only high-angle thrust activity (Berberian 1995) and that the trend of fold axes remains strikingly homogeneous throughout the area of Figure 5, showing no consistent deflections in the proximity of the buried Bala Rud fault zone. Another remarkable feature of this intensely folded area is that very few thrust faults are reported on geological maps published by the NIOC (National Iranian Oil Company; 1:100 000 scale). Within the carbonate units of the Bangestan Group thrusting is limited to the forelimbs of the Kabir Kuh, Soltan–Rit, Kurnas and Giriveh–Shirgun anticlines (Fig. 6). Field analysis and section construction indicate, however, that the amount of displacement along these faults is very limited, generally less than 1 km and not exceeding 2 km. Also, within the Shahbazan–Asmari unit thrusting is a limited phenomenon, restricted to few small displacement faults concentrated in a relatively small area south of Khorramabad city (Fig. 5).

**Fold parameterization**

The characteristics of folds in the selected area have been studied in map view to analyse their spatial arrangement, spacing and persistence. The parameters used to analyse fold distribution are the axial length and wavelength of anticlines, measured from outcrop patterns and from their axial traces. The latter were obtained from NIOC geological maps and were successively modified and integrated through the analysis of high-resolution 3D stereo (Spot5) satellite images and field surveys.

The map distribution of axial traces (Fig. 6) shows an uneven spacing between anticlines and a large variability in axial lengths. Nevertheless, three domains with an approximately homogeneous axial length and fold spacing are readily discernible in the map. Domains A and B of Figure 6 are characterized by longer axial traces than those present in domain C, and domain A clearly displays a greater spacing between anticlines than domain B or C. The same variability is reflected in Figure 7, where the anticline’s wavelength is plotted against the axial length. Anticlines of domain C display an average wavelength below 2 km and axial lengths shorter than 20 km (average 10 km). The majority of the remaining anticlines are grouped in a cluster, representing domain B of Figure 6, characterized by axial lengths between 20 and 50 km, and wavelengths between 3.8 and 7.5 km. Outside this cluster two anticlines of domain B (the Chaleh Ravgeh and Alune) have anomalously long axial lengths, and three anticlines (the Soltan–Rit, Chenareh and Kabir Kuh), which form domain A, have greater than average wavelength and axial length. The Kabir Kuh anticline, in particular, has an exceptional length of c. 200 km, which makes it the largest fold structure of the entire Zagros range. Comparing Figure 6 with the geological map (Fig. 5) it should also be noted that the large anticlines of domain A and B expose the competent units of the Bangestan Group in their cores, whereas anticlines of domain C appear to involve only the Shahbazan–Asmari carbonates. In Figure 8 two cross-sections are shown illustrating the different size and style of folds in the three domains.

**Link between fold characteristics and Mesozoic facies distribution**

As mentioned above, within the stratigraphic framework of the Lurestan Province the Late Cretaceous Bangestan Group is likely to be the rheological unit that most influences folding, because of its relatively high competence with respect to the rest of the stratigraphic succession. Therefore, to analyse the large variability displayed by the folds in the study area a comparison was made between the distribution of folds and the facies of the Mesozoic stratigraphic units. In Figure 9 the axial traces of anticlines are superimposed on the Albian–Turonian facies map compiled by Koop & Stoneley (1982), which represents the facies distribution of the Sarvak Formation. This facies map indicates that the northeastward migration of the facies boundaries, which characterizes the Early Cretaceous (Fig. 4), had brought the boundary between the neritic and the pelagic facies of the Sarvak Formation to a position that corresponds to the present northeastern flank of the Soltan–Rit anticline. This position corresponds closely to the boundary between domain A and B of Figure 6. The short wavelength of the anticlines located to the NE of the Soltan–Rit anticline (domain B) reflects the reduced competence of the Sarvak pelagic facies and the higher degree of anisotropy induced by the smaller bed thickness and frequent shale partings. Conversely, the higher competence of the carbonate platform facies (domain A) is manifested by a higher spacing between anticlines and is possibly linked to the development of thrust structures in the forelimb of anticlines (Fig. 8).

The isopachs shown on the same map (Fig. 9) indicate that across the boundary between carbonate platform and pelagic deposits there is no associated thickness variation, suggesting

![Fig. 7. Diagram comparing the wavelength and axial lengths of 42 anticlines of the southeastern Pusht-e Kuh Arc. The three highlighted clusters correspond to the fold domains defined in Figure 6. 1, Chaleh Ravgeh anticline; 2, Alune anticline; 3, Rit–Soltan anticline; 4, Chenareh anticline; 5, Kabir Kuh anticline.](image-url)
that the change in wavelength between domain A and B is exclusively a consequence of the different mechanical properties of the pelagic and neritic facies of the Sarvak Formation.

Folding behaviour of the Shahbazan–Asmari unit

The Shahbazan–Asmari unit is an erosion-resistant unit that forms the carapace of many folds in the selected area (e.g. Chenareh and Maleh Kuh anticlines). In general, good coupling is observed between the Bangestan Group level and the Shahbazan–Asmari carbonates, so that the two units fold harmonically with a concentric fold style. This is documented, for example, by the deep, pinched synclines that separate adjacent anticlines such as the Amiran–Push-te Jangal or the Soltan–Sarkan couple (Figs 5, 6 and 10). However, in an area located immediately south of Khorramabad city the style of folding of the Shahbazan–Asmari unit appears significantly different. This area, corresponding to domain C of Figure 6, is a topographic high capped by the Shahbazan–Asmari unit and Gachsaran Formation, which is positioned along the axial trend of large anticlines of the Bangestan Group with wavelengths in excess of 5 km. As shown in Figure 7, domain C is deformed by tight folds with wavelengths as short as 840 m and axial lengths less than 20 km, and by few thrust faults (Figs 5 and 8). The presence of these short-wavelength folds in the Shahbazan–Asmari carbonates, positioned along the axial traces of large Bangestan Group anticlines, indicates that the folding of the Shahbazan–Asmari level is independent of that of the underlying Bangestan Group in this region. The behaviour of the Asmari limestone, therefore, varies across the area of Figure 5 from perfectly coupled to the Bangestan Group structural level (mainly towards the SW and west) to completely decoupled from the Bangestan folds in domain C. To investigate the possible causes of this behaviour the Palaeogene stratigraphic units interposed between the Bangestan Group and the Shahbazan–Asmari carbonates have been analysed.

Palaeogene deposits

The Palaeogene section in the Lurestan Province is formed by the Amiran, Taleh Zang and Kashkan formations (Fig. 2). These deposits compose a clastic wedge filling the shallow foreland basin that formed in response to the obduction of ophiolite and radiolarite thrust sheets during the Late Cretaceous (Ricou et al. 1977; Agard et al. 2005; Homke et al. 2009). The influence that these deposits have on the development of structures was analysed through field surveys, cross-sections and the construction of isopach maps of the Amiran and Kashkan formations. The thickness data necessary to construct isopach maps were obtained using a variety of sources: field-based stratigraphic sections, published and unpublished stratigraphic logs, and remotely sensed measurements. The last were obtained using 2.5 m resolution Spot5 images associated with a 25 m resolution digital elevation model (DEM). Field-based control measurements indicate that these remotely sensed measurements have accuracy in the range of 5–15%, with the advantage of allowing a large number of measurements to be performed rapidly in remote areas of difficult access.

Amiran Formation

The stratigraphic unit displaying the largest thickness variations is the Amiran Formation. This unit occupies the area between the Chenareh and the Khorramabad anticlines (Fig. 6), and is formed by marly shales, sandstones and cherty conglomerates, displaying an overall shallowing upward trend. The isopach map of the Amiran Formation (Fig. 11a) is based on 100 thickness measurements collected throughout the area of Figure 5, wherever the base and the top of the formation are exposed. The map displays areas of maximum thickness (exceeding 1100 m) in the northeastern portion of the depositional domain, from where these deposits thin out southwestwards. The northeastern margin of the depositional domain is also characterized by thick conglomerate bodies, occupying the upper part of the section,
which display prograding geometries above the shaly lower portion. Three areas of anomalous, reduced thickness are detected in the central–eastern portion of the basin. These could be interpreted as palaeo-topographic highs indicative of an early stage of tectonic activity, as suggested by Hessami et al. (2001) and Homke et al. (2009). However, a more detailed and specific analysis is necessary to confirm this latter point.

**Taleh Zang Formation**

Above the Amiran deposits the Taleh Zang Formation is composed of carbonate-clastic deposits and reefal limestones (James & Wynd 1965). This formation is characterized by extremely variable thicknesses, ranging from 40 m to a maximum of 350 m, which vary in relation to the patchy development of the thicker reefal facies. The average thickness for the 47 measurements conducted on this formation is less than 200 m, reflecting the predominance of the carbonate-clastic facies over the thicker reefal facies. Because of the small thickness and the rapid lateral variations in these facies the possibility of drawing an isopach map of the Taleh Zang Formation was discarded. Furthermore, the reduced thickness of this formation suggests that it did not significantly influence the folding process.

**Kashkan Formation**

The Kashkan Formation is a continental succession formed by reddish cherty conglomerates, sandstones and mudstone, which extends from the northern limb of the Khorramabad anticline to the northern flank of the Chenareh anticline (Fig. 6). The isopach map of this formation (Fig. 11b) indicates that for most of the investigated area the Kashkan deposits have a thickness of less than 400 m. However, a region of marked increase in thickness is detected towards the east, where thicknesses in excess of 800 m are recorded. When compared with the isopach map of the Amiran Formation (Fig. 11a), it can be seen that this area of exceptional thickness corresponds in part to the position of the Amiran Formation depocentre. However, whereas the latter extends in a NW–SE direction across the whole of the study area, the Kashkan depocentre appears to be limited towards the NW by an area of reduced thickness corresponding to the Khorramabad and the Safid Dasht anticlines. Similarly to the anomalies found in the
distribution of the Amiran Formation, this area of thin Kashkan deposition could be interpreted as due to the presence of a palaeo-high, possibly indicating an early phase of growth of these anticlines (see also Fakhari & Soleimany 2003).

Interpretation of the folding behaviour of the Shahbazan–Asmari unit

It was observed that the folding behaviour of the Oligocene–Miocene Shahbazan–Asmari unit varies across the study area from perfectly coupled to the Bangestan Group to completely decoupled from it (Fig. 5). Two hypotheses can possibly explain this change in folding behaviour. One possibility is that a local, shallow detachment exists in the area underlying the short-wavelength anticlines; the other is that the two competent units fold disharmonically as a result of a local increase in the thickness of the incompetent units separating them, causing the Shahbazan–Asmari unit to leave the zone of contact strain of the Bangestan Group. This latter hypothesis was tested by superimposing the distribution map of axial traces on the isopach map obtained by summing the thicknesses of the Amiran and Kashkan formations (Fig. 12). This superimposition indicates that the area of tight
folding in the Shahbazan–Asmari unit (domain C in Fig. 6) corresponds to an area where the underlying Palaeocene–Eocene succession reaches a thickness between 1300 and 1600 m, which is larger than areas where a good coupling is observed between the Shahbazan–Asmari unit and the Bangestan Group. Regarding the hypothesis of a local detachment underlying the area of short-wavelength folding, the available data are insufficient to discard this option. The existence of such an extensive detachment in the Kashkan Formation appears unlikely, however, because of the frequent lateral variations that characterize these continental deposits, and also because the hypothetical detachment would also coincide with the area of increased Palaeocene–Eocene thickness.

Discussion

A wide spectrum of folding mechanisms have been proposed for the folds of the Zagros Simply Folded Belt, from pure buckling, or buckling above a detachment level, to fault-related folding, or pure forced folding (Sattarzadeh et al. 2000; Blanc et al. 2003; Sherkati & Letouzey 2004; McQuarrie 2004; Molinaro et al. 2005; Vergès et al. 2009). The most significant of these mechanisms is thought to be the buckling of the competent units that form the sedimentary cover, coupled with the occurrence and the depth of relatively weak intervals that can function as detachment levels (Sherkati et al. 2005; Carruba et al. 2006; Sepehr et al. 2006; Mouthereau et al. 2007). The existence of various detachment levels within the stratigraphic succession, which in different areas of the belt act at different depths, has often been invoked to explain the variations in fold size that can be observed across the folded belt (McQuarrie 2004; Sherkati et al. 2005; Sepehr et al. 2006).

The absence of significant thrusts in the analysed area (Fig. 5) suggests that in the Lurestan Province also the main mechanism of deformation is the buckling of competent limestone units that act as ‘control units’ or ‘structural lithic units’ governing the folding process (Currie et al. 1962; Woodward & Rutherford 1989; Price & Cosgrove 1990). This observation is further strengthened by the lack of variations in structural relief across the Simply Folded Belt; from the geological map in Figure 5 it can be seen that from the southwesternmost anticlines to the Khorramabad area, over a distance of more than 100 km across the strike of the belt, the level of exposure remains fairly constant, with the Agha Jari Formation in the deepest synclines and the Bangestan Group exposed in the core of anticlines.

The stratigraphic succession reconstructed for southeastern Lurestan (Fig. 2) indicates that the Late Cretaceous Bangestan Group and the Oligocene–Miocene Shahbazan–Asmari carbonates are the only major competent units in a succession that is otherwise dominated by clastic deposits, evaporites, shales and pelagic limestones. Our analysis of the characteristics and distribution of anticlines confirms that the Bangestan Group exerts a major control on the development of folds. In fact, the variations in facies within the Sarvak Formation appear to control the wavelength of anticlines; within this formation, the transition from pelagic to neritic facies (Fig. 9) determines a threefold increase in anticline wavelength (Fig. 7) and may also be associated with the development of thrust structures in the forelimb of anticlines.
This highlights once more the fundamental role that the mechanical stratigraphy plays in determining the modes of deformation and the final shape and size of the structures. Most importantly, the present study demonstrates that this applies not only in the vertical profile but also in plan view, as a result of the lateral changes that are inherent in a large orogen such as the Zagros range. As a consequence, caution is needed when constructing geological cross-sections to avoid interpreting changes in the fold size, which may be related to lateral variations in the mechanical properties, as changes in the depth of detachment or variations in the folding mechanism.

Some of the anticlines in the investigated area have axial lengths that are well above the average obtained from a large number of folds in the study area (Fig. 7). The Chaleh Ravgeh and Alune anticlines, both found in the pelagic facies of the Sarvak Formation (domain B of Fig. 6), and the Soltan–Rit anticline of domain A, have axial lengths of 94, 93 and 98 km, respectively, which yield aspect ratios (axial length to half-wavelength ratio) of 32, 47 and 15, above the typical values for buckle folds (<10; Price & Cosgrove 1990). In our view, the Chaleh Ravgeh and Alune anticlines represent examples of the lateral linkage of anticlines with the same trend (Sattarzadeh et al. 2000; Ramsey et al. 2008). In turn, the length of the Soltan–Rit anticline may be related to the same Late Cretaceous facies boundary that also influences fold wavelength (Fig. 9). The influence of facies variations on the distribution of structures was analysed in a series of experiments performed by Dixon (2004) using analogue models. The experimental results indicated that strain concentrates along the transition between the relatively rigid carbonate platform and the less competent basinal deposits, giving rise to the early development of folds, which consequently attain above-average lengths.

A different aspect of mechanical stratigraphy, linked to the thickness of incompetent units, is illustrated by the folding behaviour of the Shahbazan–Asmari unit. The fact that decoupling in the Shahbazan–Asmari unit occurs only where the underlying Palaeocene–Eocene succession exceeds 1300 m thickness (Fig. 12) indicates that beyond this distance the strain transmitted from the buckling Bangestan Group is insufficient to influence the folding of the Shahbazan–Asmari carbonates; in other words, the Shahbazan–Asmari unit is outside the zone of contact strain of the Bangestan Group. The extent of the zone of contact strain of the Bangestan Group. The extent of the zone of...
contact strain of a competent layer surrounded by a Newtonian viscous matrix was originally quantified as one wavelength distance from the median line of the buckling unit (Ramburg 1961). However, from observation of natural multilayers Price & Cosgrove (1990) inferred that at a distance corresponding to 20–25% of the wavelength the influence of the buckling layer on other competent units becomes negligible. Our results, indicating that folding of the Shahbazan–Asmari unit becomes independent of the underlying folds of the Bangestan Group (4–6 km wavelength, Fig. 7) when a thickness of 1.3 km is interposed between the two units (Fig. 12), are in good agreement with this latter observation.

Conclusions

The analysis of anticline distribution in the southeastern Lurestan region provides direct evidence of the impact that the mechanical properties of units forming a geological multilayer have on the folding process. In southeastern Lurestan the stratigraphic succession, both the exposed section and in the subsurface (Fig. 2), is dominated by incompetent units (i.e. shales, clastic deposits, evaporites, pelagic limestones) in which the carbonate platform deposits of the Bangestan Group and the Shahbazan–Asmari unit stand out as topography-forming units. The analysis of fold distribution, measured in terms of axial length and wavelength, indicates that these two units correspond also to the competent units that control the folding behaviour in this region. The control exerted by the Late Cretaceous Bangestan Group is demonstrated by the threefold increase in fold wavelength that accompanies the transition from pelagic to neritic facies of the Sarvak Formation (Figs 7, 9 and 13). For the Shahbazan–Asmari unit, its reduced thickness and its proximity to the thicker Bangestan Group imply that it folds harmonically with this latter dominant unit. However, where the thickness of the less competent units (Palaeogene deposits) interposed between the Shahbazan–Asmari and the Bangestan Group exceeds a critical value, estimated to be 1300 m, the Shahbazan–Asmari carbonate unit deforms independently of the underlying Bangestan Group. This generates shallow geometries that do not reflect the deeper deformation (Fig. 13).

A similar, well-documented, decoupling occurs in the oil-rich Dezful Embayment (Fig. 1), where the high mobility of the thick Gachsaran evaporite allows the overlying Agha Jari deposits to fold disharmonically from the underlying Shahbazan–Asmari carbonates (O’Brien 1950; Sherkati et al. 2005; Carruba et al. 2006). These two examples suggest that decoupling levels play an important role during the deformation of geological multilayers that are characterized by alternating units with different mechanical properties, such as in the Zagros, allowing independent deformation below and above them. As already suggested by Sepehr et al. (2006), understanding of the conditions, the geometries and the structures that allow decoupling to occur may prove fundamental in the future exploration of the Zagros folded belt. This is the case particularly for the prospective, gas-rich, Dalan Formation (Bordenave 2008), which is sandwiched between the thick evaporite-rich Dashtak Formation (Fig. 2) and the predominantly clastic formations of the early Palaeozoic.

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