Basin architecture and growth folding of the NW Zagros early foreland basin during the Late Cretaceous and early Tertiary

EDUARD SAURA1*, JAUME VERGÉS1, STÉPHANE HOMKE2, ERIC BLANC3, JOSEP SERRA-KIEL4, GILEN BERNOLA5, EMILIO CASCIELLO1, NAIARA FERNÁNDEZ1, INDIANA ROMAIRE1, GIULIO CASINI2, JEAN CHRISTOPHE EMBRY2, IAN R. SHARP2 & DAVID W. HUNT2

1Group of Dynamics of the Lithosphere (GDL), Institute of Earth Sciences ‘Jaume Almera’, CSIC, Solé i Sabaris, s/n, 08028, Barcelona, Spain
2Statoil Research Centre, Sandsliiveien 90, Bergen, PO Box 7200, N-5020 Bergen, Norway
3Statoil ASA, Drammensveien 264, Vækerø, N-0246 Oslo, Norway
4Department of Stratigraphy, Palaeontology and Marine Geosciences, University of Barcelona, 08028 Barcelona, Spain
5Department of Mining and Metallurgic Engineering, University of the Basque Country, E-48901 Barakaldo, Spain

*Corresponding author (email: esaura@ictja.csic.es)

Abstract: We present and use the chronostratigraphy of 13 field logs and detailed mapping to constrain the evolution of the early Zagros foreland basin, in NW Iran. Large foraminifera, calcareous nannofossil, palynological and 87Sr/86Sr analysis supplied ages indicating a Campanian–early Eocene age of the basin infill, which is characterized by a diachronous, southwestward migrating, shallowing upwards, mixed clastic–carbonate succession. Growth synclines and local palaeoslope variations indicate syndepositional folding from Maastrichtian to Eocene time and suggest forelandward migration of the deformation front. We also illustrate the basin architecture with a synthetic stratigraphic transect. From internal to external areas, time lines cross the formation boundaries from continental Kashkan red beds to Taleh Zang mixed clastic–carbonate platforms, Amiran slope deposits and basinal Gurpi–Pabdeh shales and marls. The foreland basin depocentres show a progressive migration from the Campanian to Eocene (c. 83–52.7 Ma), with rates of c. 2.4 cm a⁻¹ during the early–middle Palaeocene (c. 65.5–58.7 Ma) increasing to c. 6 mm a⁻¹ during the late Palaeocene–earliest Eocene (c. 58.7–52.8 Ma). Coeval subsidence remained at c. 0.27 mm a⁻¹ during the first 12.7 Ma and decreased to c. 0.16 mm a⁻¹ during the last 4.2 Ma of basin filling. Finally, we integrate our results with published large-scale maps and discuss their implications in the context of the Zagros orogeny.

Supplementary material: Tables with dating results are available at http://www.geolsoc.org.uk/SUP18439.

Foreland basins are dynamic systems in which different sedimentary units vary across time and space as a response to pulsed and migratory tectonic activity. Many examples of the relationship between fold belt evolution and the spatial–temporal distribution of concomitant foreland basins have been described in the literature. The cases of the Alps (Allen et al. 1991; Sinclair et al. 1991) and the Pyrenees (Puigdefabregas & Souquet 1986; Vergès et al. 1998) are well known. In these examples, the variability across time of the stratigraphic sequence is controlled by the interaction between eustasy, tectonics and sediment supply. As a consequence, most of lithostratigraphic formations described in foreland basins have turned out to be diachronous (e.g. James & Wynd 1965; Burbank et al. 1992).

The Zagros mountain range (Fig. 1) is a segment of the Alpine–Himalayan system formed along the Arabia–Eurasia collision zone (e.g. Berberian & King 1981; Golonka 2004), following the closure of the Neo-Tethys ocean (e.g. Barrier & Vrielynck 2008). In the Zagros domain, this process occurred in two major stages. Initially, obduction of radiolarite and ophiolite slices on top of the NE Arabian passive margin occurred during the Late Cretaceous (Ricou 1971; Gidon et al. 1974; Alavi 1994). Subsequently, final oceanic closure and Arabia–Central Iran continental collision took place (e.g. Braud 1987). Ages ranging between the Eocene (Braud 1987; Sengör et al. 1993) and the late Miocene (Stoneley 1981; McQuarrie et al. 2003) have been proposed for the initiation of this stage. However, recent studies have consistently documented the late Oligocene–early Miocene age of this stage (Agard et al. 2005; Fakhari et al. 2008). After the onset of collision, the deformation front propagated towards the foreland (Emami 2008; Khadivi et al. 2009), reaching the front of the Lurestan Arc and the Mesopotamian foreland basin at about 7.6 ± 0.5 Ma (Homke et al. 2004).

The occurrence of a Late Cretaceous–early Cenozoic tectonic stage related to ophiolite emplacement has long been recognized (e.g. James & Wynd 1965; Gidon et al. 1974; Ricou et al. 1977; Berberian & King 1981), although its precise timing and character have been addressed only recently (Fakhari & Soleimany 2003; Sherkati et al. 2006; Blanc et al. 2008; Homke et al. 2009). In Lurestan Province, an early foreland basin (Amiran Basin; Homke et al. 2009) formed during this period by flexure of the Arabian Plate lithosphere in front of an obducted ophiolite complex. Currently, the Amiran Basin has a width of c. 140 km and a length exceeding 550 km (Farzipour-Saein et al. 2009; Homke et al. 2009). To the hinterland, the basin was uplifted to a maximum of 1300 m of structural relief probably as a result of thrusting (Homke et al. 2009). The infill of this early foreland basin consists
of a thick mixed siliciclastic–carbonate sedimentary succession (Amiran–Taleh Zang–Kashkan succession; Fig. 2), with marked changes in thickness, sedimentary hiatuses and angular unconformities that have been attributed to both large-scale tectonics and early folding (Casciello et al. 2009; Homke et al. 2009). The SW boundary of the Amiran Basin runs parallel to the northern flank of the large Kabir Kuh anticline, which was interpreted as the basin forebulge by Alavi (2004).

The main objectives of the present study are three-fold: (1) to define the architecture of the Amiran Basin in the NW Zagros Fold Belt (Lurestan Province) integrating the main findings by Homke et al. (2009) with 12 new outcrop-based stratigraphic logs constrained by more than 350 samples analysed using various techniques; (2) to confirm and constrain early folding coeval with the Amiran Basin proposed by Homke et al. (2009); (3) to discuss the implications of such early foreland basins in the context of the Zagros orogeny from Kurdistan to Oman, integrating our results with reconstructed large-scale maps. Finally, the Amiran Basin is sandwiched between the two major hydrocarbon reservoirs of the area, the Cretaceous Sarvak Formation and the Miocene Asmari Formation. The geometry and evolution of the Amiran–Taleh Zang–Kashkan succession is thus directly relevant for hydrocarbon prospectivity in this still little explored region.

**Geological framework and stratigraphic succession**

The Zagros Mountains can be divided into five NW–SE-trending tectonic domains (Fig. 1): the Urumieh–Dokhtar volcanic arc, the metamorphic Sanandaj Sirjan Zone, the Imbricated Zone, the Simply Folded Belt and the Mesopotamian–Persian Gulf foreland basin. The Simply Folded Belt, the main subject of this study, has a 10–12 km thick sedimentary cover (Falcon 1974; Colman-Sadd 1978), mainly deformed by buckling and subsidi-
The 10–12 km thick stratigraphic succession of Lurestan Province includes the Palaeozoic and Mesozoic Arabian passive margin deposits and the Cenozoic sedimentary infill of the Zagros foreland basin (Fig. 2). The Mesozoic passive margin deposits consist of limestones, marls and evaporites deposited from Triassic to Late Cretaceous time. The Cenozoic sedimentary pile is formed by two siliciclastic sequences separated by the Miocene carbonate Asmari Formation. The lower clastic sequence is the subject of this study and is described below. In the study area, the upper clastic unit is formed by the c. 800 m thick Gachsaran evaporites and interbedded clastic deposits covered by the 3–4 km thick, non-marine Agha Jari and Bakhtyari formations.

Passive margin conditions ended in the study area during the deposition of the Gurpi Formation, characterized by c. 350 m of dark blue–grey marly shales with subordinate marly limestones of Campanian–Palaeocene age (James & Wynd 1965). The Amiran Formation is a detrital formation, mainly formed by dark olive brown silts and sandstones mainly composed of detrital ophiolite material, deposited in a roughly southwestward wedging basin (James & Wynd 1965), with marked local changes in thickness (Casciello et al. 2009). Overlying the Amiran Formation, the Taleh Zang Formation is a carbonate-dominated formation formed by interlayered limestone, marls, shales and bioclastic sandstones deposited in a shallow-water environment (James & Wynd 1965). Above, the Kashkan Formation is a predominantly continental, red-coloured unit with shales, sands and conglomerates, mainly sourced from the radiolarite–ophiolite complexes of the Imbricated Zone (James & Wynd 1965).

The whole Amiran–Kashkan succession grades southwestwards into the Pabdeh Formation, a stratigraphic unit formed by grey shales and thin argillaceous limestones. Within this formation, the Purple Shale Member consists of purple red–grey shales (James & Wynd 1965). The carbonate platforms of the Shahbazan and Asmari formations cover the Palaeogene succession. The Shahbazan Formation consists of medium-beded sucrosic dolomite and dolomitic limestone, disconformably overlain by the Asmari Formation, which is formed by limestone beds with shelly intercalations (James & Wynd 1965). Homke et al. (2009) reconstructed the basin geometry and illustrated the diachronicity of the lithostratigraphic formations of the Amiran Basin by combination of their own ages of the Gurpi–Shahbazan succession in the Amiran anticline with previously published data.

### Stratigraphy of the Amiran Basin

To complete the sedimentological characterization and dating of the Amiran Basin 12 new stratigraphic sections were measured between the Khorramabad and Chenareh anticlines: Dar Howz, Ali Abad, Cehel Taghi, NE Push-t-e Jangal, SW Push-t-e Jangal, Sarkan, SW Sultan, NE Sultan, NE Rit, SW Rit, Kush Ab and NE Chenareh (Figs 3 and 4). Additional stratigraphic and structural data were collected in other localities of the basin. More than 350 samples were collected systematically in all logged sections for dating. Bioclastic and fossiliferous limestones and sandstones of all formations were sampled for dating using
large benthic foraminifera. Marlstones and marly limestones were sampled for calcareous nannofossil analysis throughout the marine formations of most of the studied sections. Strontium isotope dating \((^{87}\text{Sr}/^{86}\text{Sr})\) was performed using samples of marine limestone in the Laboratorio de Geocronología y Geoquímica Isotópica of the Universidad Complutense de Madrid in Spain. Palynological dating was performed from samples of shales and marls of the Gurpi, Amiran, Taleh Zang and Kashkan formations.

The Gurpi and Pabdeh formations

The distinction between Gurpi and Pabdeh units was established in the Khuzestan and Fars areas, where they have different lithologies and are separated by a depositional hiatus (James & Wynd 1965). In the Lurestan area, the differentiation is mainly based on their age and the occurrence of marly limestones of the Emam Hassan Member in the Upper Cretaceous Gurpi Formation and the Purple Shales Member at the base of the Pabdeh Formation. The Emam Hassan Member was not identified in the northern part of the basin, and the Purple Shales Member was observed only in its southern part, in the Sultan-Rit and Chenareh anticlines (Fig. 4).

The Amiran Formation

The Amiran Formation is the most extensive formation of the Amiran Basin. It occurs in all measured stratigraphic sections and displays significant thickness variations (Fig. 4). Two members have been distinguished within the Amiran Formation, the Amiran Conglomerates (Fig. 5a), on the NE border of the basin, and the Amiran shales or Amiran Formation sensu stricto (Fig. 5b).

Along the NE flank of Khorramabad anticline (Fig. 3) the contact between the Gurpi and Amiran formations is transitional and is characterized by a thick shaly succession with interlayered thin sandstone beds deposited on the basin floor and slope. In the central part of the Khorramabad anticline, the thickness of the Amiran shales exceeds 750 m (Fig. 4). Above the Amiran shales, the Amiran conglomerates show significant thickness variations along the strike of the anticline, with a maximum measured thickness of 600 m in the west (Fig. 4). The conglomerates are constituted by polymictic mainly clast-supported beds, containing poorly sorted, subrounded pebbles of radiolarite and dunite and subsidiary chert, limestone, quartz, and microconglomerate. Grain sizes range from sand to 20 cm in diameter. The conglomerate member is formed by interfingering fan deltas with frequent Gilbert delta geometries (i.e. well-defined toesets, foresets and topsets). In the western area, well-exposed foresets have a height of c. 60–80 m and palaeoslopes are up to 17°. The fan delta complexes can be traced around the SE closure of the Khorramabad anticline, until they downlap, thin and disappear in the central segment of the SW limb of the anticline.

Southwards, on the NE limb of the Pusht-e Jangal anticline (Fig. 3), the base of the Amiran Formation is also transitional. In this area, the Amiran Formation has a thickness of 910 m
Fig. 4 and comprises dark shales and marls with subsidiary sandstone layers and very rare conglomeratic levels with radiolarite, chert, limestone and dunite pebbles. Slump structures and channelized sandstones observed along the whole section suggest an unstable or bypass slope depositional setting. In the upper part of the Amiran Formation sandstones with bioclasts and bioclastic limestones are very frequent, overlain by chaotic layers composed of large blocks (c. 1 m diameter) of limestone with corals. On the SW limb of the anticline, the Amiran Formation has a thickness of c. 1300 m (400 m more than on the NE limb; Fig. 4) and is mostly formed by black marls, shales and siltstones, with common sandstone and conglomerate beds in the central part of the section. In the upper part of the sequence, thin (<10 cm) limestone layers are abundant. Particular to this area is the occurrence of a carbonate interval located about 400 m above the Gurpi–Amiran transition. This is a 10–20 m thick interval, characterized by a chaotic member at its base, mainly composed of blocks of marly layers, overlain by massive, discontinuous limestone blocks, which frequently appear internally folded. This interval is continuous around the Pusht-e Jangal anticline, pinching out at the base of the Taleh Zang Formation on the NE limb of the anticline. We interpret this unit as being formed by the gravitational collapse of an unstable platform. In the Amiran anticline, the Amiran Formation is 810 m thick, with a stratigraphic succession very similar to that on the SW limb of the Pusht-e Jangal anticline (Homke et al. 2009; Fig. 4).

Southwards, in the Sultan Anticline (Fig. 3), the base of the Amiran Formation is transitional from the Purple Shales Member. The formation has a thickness of 775 m and is mostly formed by black shales with subordinate sandstone layers with abundant bioclasts, which are more frequent in the upper part of the section (Fig. 5b). Slump structures are frequent at the base of the section. The top of the Amiran Formation is transitional with the shallow-marine Taleh Zang formation. Towards the SE, in the
The Taleh Zang Formation

In this section we describe the spatial distribution of the mixed carbonate–clastic predominantly shallow-marine beds observed across the Amiran Basin, between the Amiran flysch and the continental red beds of the Kashkan Formation. This unit is discontinuous and in the northern part of the basin has been mapped and dated based on its fossil record as the Tarbur Formation (James & Wynd 1965), characteristic of the Fars area. These outcrops correspond to a 5 m thick transgressive carbonate platform developed over flat-lying delta-top fluvial and flood plain palaeosols. This limestone can be traced c. 10 km along the NE limb of the Chenareh anticline, laterally pinching out, and it does not crop out in the SE part of the anticline, although it can be seen in the Bakhtyari culmination, north of the Dezful embayment. Southwestwards, the closest outcrops of the Taleh Zang Formation are located in the Zangul and the Pusht-e Jangal anticlines. From this point to the south, its base is gradational, marked only by the appearance of thin bioclastic limestone beds. On the NE limb of the Pusht-e Jangal anticline, the Taleh Zang Formation comprises a c. 200 m thick massive limestone unit with Rhodophyceae and reefal facies (Fig. 4). These units grade laterally into a thinner marly sequence containing large blocks (c. 10 m) of the same limestones. In contrast, the Taleh Zang Formation on the SW limb of the Pusht-e Jangal anticline is defined by a more clastic <10 m thick interval (Fig. 4) with marls and mudstones in the upper part. To the south, on the NE limb of the Amiran anticline, the Taleh Zang Formation is c. 190 thick (Fig. 4), composed of decimetre- to metre-scale bioclastic limestone, dark mudstone–siltstone, and brown sandstone beds containing reef-derived bioclasts (Homke et al. 2009). In the Sarkan and Sultan anticlines, the Taleh Zang Formation, with a thickness between 150 and 200 m (Fig. 4), shows a very similar succession to that in the Amiran anticline, although fragments of large benthic foraminifera are more frequent. In the Rit anticline, the Taleh Zang Formation displays different characteristics on both limbs. On the NE limb it has a thickness of 250 m and is defined by a massive basal member formed by metre-thick limestone layers with interbedded marly beds, which become dominant up-sequence (Fig. 4). In contrast, the succession on the SW limb is characterized by a basal part of alternating metre-thick marls and nodular, bioclastic limestones and an upper part with thick massive bioclastic limestone. Along the Kush Ab valley, these beds show spectacular outcrop-scale, low-angle southwestward prograding clinoforms (Figs 5c and 6). The clinoform topsets are 1–2.5 km long, with a gentle mostly prograding edge. Foreset length allows us to estimate a palaeobathyometry of around 350 m in this part of the basin. Finally, in the Chenareh area, the Taleh Zang Formation is defined by a 20 m thick massive bioclastic limestone (Fig. 4).

The Kashkan Formation

The continental deposits of the Kashkan Formation also display significant thickness and facies variations across the Amiran Basin (Fig. 4). Along the NE border of the basin, the Kashkan Formation is very irregularly distributed, with a maximum local thickness of c. 500 m but pinching out below the Shahbazan Formation northwards. Around the Khorramabad anticline, the Kashkan Formation displays alluvial plain facies with a transitional base to the marine Amiran Formation. In the Dar Howz area, the base of the Kashkan Formation is characterized by red beds with channelized conglomerates incised into well-developed palaeosols. These beds are interpreted to form a relatively thin (30–40 m) alluvial topset facies to the underlying Gilbert deltas. Moving up section in the Kashkan Formation, the conglomerate-filled channels decrease, and are overlain by rooted mud and silt-filled channels. These facies are abruptly overlain by an interval with well-developed caliche horizons and then by green–grey mudstones, siltstones and fine-grained sandstones. The interval above the caliche is best interpreted as having been deposited in an overall transgressive, poorly drained or swampy coastal plain setting. This interval is overlain abruptly by the Tarbur Formation, which can be interpreted as the climax of a regional Maastrichtian transgression. This platform is subsequently covered by a 360 m thick interval with reddish shales and subordinate reddish and greenish sandstones, which define a new interval of palaeosols of the Kashkan Formation (Fig. 4). In the Cehel Taghi area, two conglomeratic beds can be differentiated within the basal palaeosols, mainly formed by carbonate and subsidiary chert clasts. These layers are well sorted with very well rounded clasts. Low-angle planar, swaley and trough cross bedding is present. A carbonate matrix, blocky marine isopa-
The Shahbazan and Asmari formations

The Amiran Basin is sealed by the Shahbazan and Asmari formations. On the NE limb of the Khorramabad anticline the Shahbazan Formation is mostly formed by a 50–80 m thick carbonate interval with several metre-thick, shallow-water platform top cycles. The Shahbazan Formation is mostly bioclastic at the base and dolomitic at the top, where microkarstic features and hardgrounds become frequent, at the top of the platform cycles. Corals are locally present. The basal contact of the Shahbazan Formation is poorly exposed, but a mixed carbonate-clastic interval can be seen to sit abruptly on a basal well-sorted conglomerate. A shallow-water mixed carbonate-clastic platform top setting is envisaged for the Shahbazan Formation in this location, with periodic exposure. Southwards, from the Pusht-e Jangal to the Chenareh anticlines, the Shahbazan Formation becomes formed by well-bedded, fine-grained, whitish, dolomitic mudstones, with a maximum measured thickness of c. 160 m in the Amiran anticline. On the NE boundary of the basin, the base of the Shahbazan Formation lies with an angular unconformity on top of the Amiran Conglomerates and becomes rapidly paraconformable to the south on top of the Kashkan Formation along the studied transect. The contact between the Kashkan and Shahbazan formations is usually sharp, and in the Amiran anticline purple coloration and palaeolsols strongly suggest the presence of a sedimentary hiatus (Homke et al. 2009). However, this contact may be locally transitional (Fig. 5d) and growth strata patterns involving the Shahbazan Formation have been observed towards the east.

The Asmari Formation paraconformably overlies the Shahbazan Formation. In the Khorramabad area (Dar Howz section), the contact is defined by a well-developed palaeokarst. The top surface of the Shahbazan Formation is jointed, and the joints are karstified and solution enlarged, with the fractures filled with material derived from the overlying Asmari Formation. Super-imposed on the karst is a well-developed submarine hardground association characterized by Lithophaga borings, corals and encrusting red algae that mark the return to marine conditions during deposition of the Amari Fm. The Asmari Formation displays an overall deepening up-sequence trend, with frequent and more diverse fauna in its upper part. Oysters, rhodoliths, branching corals and coated grains are common in the Dar Howz section, as is plant debris in marly breaks. Local bioclastic sandwaves and channels can be identified. A platform top shallow-marine setting is envisaged, with periodic clastic input.

In the Pusht-e Jangal anticline, the base of the Asmari Formation is defined by a bioclastic mudstone with corals and very rare foraminifera. In the Amiran anticline, the contact is defined by an erosive unconformity, above which the succession is formed by bioclastic limestones (Homke et al. 2009).

Chronostratigraphy of the Amiran Basin

Late Cretaceous (Campanian–Maastrichtian, c. 83.5–65.5 Ma)

The oldest dated foreland basin deposits correspond to the Late Cretaceous and are located around the SE closure of the Khorramabad anticline. On the NE limb of this anticline, the Gurpi Formation at the base of the Cehel Taghi section contained an early Campanian calcareous nanofossil assemblage (Zone CC25a) (Fig. 7). The following dated sample contained the same early Campanian assemblage, and is located c. 140 m above, within the Amiran Formation. Towards the NW, on the NE limb of the Khorramabad anticline, the transgressive Tarbur Formation contains rudist (in situ radiolitids and hippuritids), nerinid gastropod and benthic foraminifera (Orbitoides sp., Lufotis sp.) indicating a Maastrichtian age. The correlation of this level with the beach deposits of the Kashkan Formation in the Cehel Taghi hill as well as interfingered fan deltas allows us to assume a Late Cretaceous age for the Amiran Formation and the basal interval of the Kashkan Formation along the NE Khorramabad anticline (Fig. 7).

The Maastrichtian is well characterized around the Pusht-e Jangal anticline (Fig. 7). On its NE limb, this interval has a minimum thickness of 600 m, with the Gurpi–Amiran transition assigned to calcareous zone CC25a. On the SW limb, this interval has a minimum thickness of 200 m with the Gurpi–Amiran transition probably slightly younger (CC25a–CC25b). Maastrichtian calcareous nanofossil assemblages were also recorded in several samples of the Gurpi Formation at the basal part of the Amiran and Sultan sections (Homke et al. 2009; Fig. 7).

Early Palaeocene (Danian, c. 65.5–61.7 Ma)

On the NE limb of the Pusht-e Jangal anticline, the basal Danian is well preserved with two samples located c. 720 m and c. 860 m above the Gurpi–Amiran transition assigned to zones NP1 and NP2, respectively (Fig. 7). Furthermore, the lack of larger foraminifera in the Taleh Zang limestones is in agreement with a Danian–Selandian age for these layers, as it
can be correlated with the well-known extinction event after the K–T boundary, and therefore we have located the top of the Danian within this formation. As a result, the minimum calculated thickness for this interval is of 300 m. In the Sultan and Amiran sections, the Danian is characterized by either the lack or condensation of zones NP1 and NP2 (Fig. 8) (Homke et al. 2009). In the Amiran section, the Gurpi–Amiran transition occurs during this period, whereas in the Sultan area only the Gurpi Formation was deposited during this period (Fig. 7). Finally, in the southern boundary of the study area, three samples from the Gurpi Formation located at 0, 20 and 40 m from the base of the NE Chenareh section were respectively assigned to zones NP2, NP3 and basal NP4. These intervals correspond to the Danian, which implies that at least 40 m of the Gurpi Formation above the Emam Hassan Member were deposited during the early Palaeocene in the Chenareh area.

Middle Palaeocene (Selandian, c. 61.7–58.7 Ma)

Selandian calcareous nannofossil assemblages were found in most sections of the southern part of the basin (Fig. 7). On the SW limb of the Push-t-e Jangal anticline, a sample containing calcareous nannofossils from zone NP5 was collected 440 m above the Gurpi–Amiran transition. In the Amiran area, the Selandian deposits correspond to most of the Amiran Formation and have a thickness of c. 550 m. On both limbs of the Sultan anticline, less than 80 m of sediment were deposited during this period, which coincides with the Gurpi–Amiran transition. At the base of the NE Rit section, the Purple Shale Member corresponds to zone NP4. Southwards, in the SW Rit and NE Chenareh logs, the contact between the Gurpi Formation and the Purple Shales Member has been assigned to zone NP5 and one sample collected 20 m below this transition in the Chenareh anticline supplied a calcareous nannofossil assemblage corresponding to the Selandian (zone NP4). The maximum calculated thickness for the Selandian period in the Chenareh anticline is 50 m.

Late Palaeocene (Thanetian, c. 58.7–55.8 Ma)

The Thanetian is the most extensive stage of the southern part of the basin (Fig. 7). In the Amiran anticline, this interval is well constrained by the large foraminifera within the Taleh Zang Formation (Homke et al. 2009). However, the base of the Thanetian is not precisely dated because of the lack of calcareous nannofossil assemblages in the samples collected in the upper part of the Amiran Formation, which is a characteristic feature of the middle and upper parts of this formation. Similarly, the top of the Thanetian could not be dated with precision. However, Homke et al. (2009) calculated a thickness of c. 400 m assuming a constant sedimentation rate for this interval, which encompasses the upper part of the Amiran Formation, the Taleh Zang Formation and the lower part of the Kashkan Formation. Thanetian large foraminifera (Ranikothalia) were also observed in the Taleh Zang Formation on both limbs of the Sarkan anticline. In the Sultan area, the base and top of the Thanetian are precisely located after a tightly characterized calcareous nannofossil zone sequence at the base and the recognition of the characteristic calcareous nannofossil assemblage of the Palaeocene–Eocene boundary Thermal Maximum at the top. The whole interval has a thickness of c. 500 m within the layers of the Amiran Formation. Towards the SE, on the NE Rit anticline, the Thanetian is less well constrained owing to a lower number of samples successfully dated. Furthermore, four samples dated using palynostratigraphy supplied Eocene ages, which seem to be too young when compared with other dating results. The Thanetian interval is thus constrained at the base by a calcareous nannofossil assemblage corresponding to zone NP7 and at the top by Thanetian large foraminifera collected at the top of the Taleh Zang Formation and the early Eocene pollen content of the base of the Kashkan Formation. Therefore, in this area this stage embraces c. 750 m of sediments of the Amiran and Taleh Zang formations (Fig. 7).

In the Kush Ab area, between the SW Rit and NE Chenareh sections, the Thanetian is characterized by the occurrence of a sedimentary hiatus at the base (Fig. 8). In SW Rit a sample of the Amiran Formation collected 3 m above a sample of the Purple Shale Member corresponding to zone NP6 contained
calcareous nannofossils corresponding to zone NP9. This implies a hiatus of \(c. 1.2\) Ma (Fig. 7). A similar situation can be observed in the Chenareh section, where two samples from the Gurpi Formation and the Purple Shale Member separated by 20 m have been assigned to zones NP5 and NP8, implying a potential hiatus of \(c. 1\) Ma. In SW Rit, the top of the Palaeocene is located between a bioclastic sandstone of the upper part of the Amiran Formation with Thanetian foraminifera and the base of the Taleh Zang Formation with early Ypresian foraminifera (Fig. 7). Also, in the Chenareh anticline, the top of the Thanetian is located between a bioclastic sandstone with Thanetian foraminifera and a marly layer containing an Ypresian calcareous nannofossil assemblage. Both layers correspond to the Purple Shale Member of the Pabdeh Formation. This implies a dramatic thinning of the Thanetian deposits along the Kush Ab valley, from \(c. 500\) m to \(c. 30\) m in 12 km, associated with the Purple Shales–Amiran transition and a potential sedimentary hiatus (Fig. 7). In this area, palynostratigraphic and strontium isotope ages indicating an early Eocene age were mostly in disagreement with the calcareous nannofossil and foraminifera ages. Although already incipient in previous deposits, a characteristic feature of the Thanetian deposits is the frequent occurrence of reworked Late Cretaceous calcareous nannofossil assemblages.

**Early Eocene (Ypresian, \(c. 55.8–48.6\) Ma)**

Ypresian sediments have been identified only to the south of the Amiran anticline. When possible, two stages have been differentiated within this interval: Ilerdian (\(c. 55.8–52.8\) Ma) and Cuisian (\(c. 52.8–48.6\) Ma) (Fig. 7). In the Amiran anticline, the uppermost \(c. 150\) m of the Kashkan Formation were dated as early Eocene (Homke et al. 2009). In the SW Sultan anticline, an Ypresian age can be assumed at least up to the base of the Kashkan Formation, containing a palynological assemblage corresponding to the early Eocene. According to large foraminifera and strontium isotope ages the transition between the Ilerdian and the Cuisian should be located within the Taleh Zang Formation. On the NE limb of the Sultan anticline, early Ilerdian foraminifera were observed in several bioclastic sandstones of the upper part of the Amiran Formation, and middle Ilerdian foraminifera within the Taleh Zang Formation. Also, on the NE limb of the Rit anticline, the palynological assemblage locates the base of the Eocene at the base of the Kashkan Formation. In the SW Rit anticline, the base of the Eocene is located in the uppermost layers of the Amiran Formation and Ilerdian fauna was found in two samples collected in the Taleh Zang Formation. Strontium isotope ages combined with large foraminifera suggest that the base of the Cuisian is located within the Taleh Zang Formation (Fig. 7). In the Kush Ab valley, the Ilerdian is accurately dated with calcareous nannofossil assemblages corresponding to zones NP11 and NP12 in its lowermost part and Ypresian large foraminifera collected immediately above. As only the lowermost part of zone NP12 corresponds to the Ilerdian, the transition to the Cuisian must be located within the Amiran shales. Up-sequence, the bioclastic limestones of the Taleh Zang Formation contain Cuisian foraminifera, in agreement with the obtained isotopic ages (Fig. 7). Finally, in the Chenareh anticline, the combination of biostratigraphy and isotope stratigraphy allows a precise dating of the Ilerdian and Cuisian intervals. At the base of the section, in the Purple Shale Member, a sample contained a calcareous nannofossil assemblage corresponding to the Ilerdian part of zone NP12. Approximately 70 m above, already in the basal part of the Amiran Formation, a sample was dated as Ilerdian by its isotopic composition, and immediately above a sample contained a typical assemblage corresponding to the Cuisian interval of zone NP12. Up-sequence, all samples consistently indicated a Cuisian age up to the contact with the Shahbazan Formation (Fig. 7). According to the presented data, the Ilerdian has a relatively constant and low thickness (\(<400\) m) across the entire area, whereas the Cuisian shows a significant increase in thickness along the Kush Ab valley, reaching a maximum of \(c. 1000\) m in the Chenareh anticline. As in the Thanetian deposits, reworked Late Cretaceous calcareous nannofossil assemblages are abundant in the Ypresian successions.

**Middle Eocene–Miocene**

The middle and upper Eocene (\(c. 48.6–32\) Ma) deposits are the least constrained of the Amiran Basin. In the SW Sultan section
a sample collected close to the top of the Kashkan Formation was dated as early-middle Eocene based on its palynological content. Furthermore, the strontium isotope composition of a sample collected 20 m below gave possible age ranges of 42.83–45.78 Ma and 34.24–35.64 Ma. Only the older range overlaps with the obtained petrostratigraphic age, which implies a middle Eocene age for this interval. In the NE Rit, a sample collected at the top of the Kashkan Formation contained a pollen assemblage not younger than middle Eocene. Middle to upper Eocene sediments have not been observed in the remaining sections. The ages presented above for the uppermost intervals of the Kashkan Formation suggest much reduced to non-existent middle-upper Eocene successions.

The base of the Shahbazan Formation has been dated with strontium isotope analyses in seven sections (Fig. 7). Most of the ages range from 37 to 30 Ma (Priabonian–Rupelian). Although some of the samples give older potential ages (up to 42.15 Ma), the consistency between samples from different sections across the basin suggests that these values are less correlatable, and thus we consider the younger ones as the most plausible. Furthermore, additional samples collected from some metres above the basal contact in several sections and dated with the same method have early Oligocene ages. Therefore, we believe that the base of the Shahbazan Formation in the Amiran Basin can be consistently dated as being close to the Eocene–Oligocene boundary.

In Khorramabad anticline, where the contact between the Shahbazan and Asmari formations is clear, two samples collected above and below the contact gave isotopic ages of 27.20–28.10 Ma and 19.82–20.29 Ma, respectively. However, two dated samples from intermediate levels of the Shahbazan Formation are not consistent with these ages, preventing a definite acceptance or rejection of the age of the top of the Shahbazan Formation, especially given the karstic features observed in the intermediate cycles of the Shahbazan Formation. The youngest dated sample corresponds to a limestone bed located at the top of the Asmari Formation on the NE limb of the Khorramabad anticline, with an isotopic age of 19.14–19.51 Ma (Early Miocene) in agreement with the early-middle Miocene large foraminifera assemblage observed in this area and the NE Amiran anticline (Homke et al. 2009).

Late Cretaceous–Early Eocene folding

The most intense Zagros folding stage occurred during the Miocene, largely masking any early history of folding. In a few places, however, growth strata patterns unambiguously document folding development synchronous with the filling of the Amiran Basin. Uplift in the internal parts of the basin is also recorded by the large amount of reworked Late Cretaceous calcareous nanofossil assemblages across the foreland basin but mainly in the Thanetian and Ypresian sequences. In this section we present three of the most prominent examples of tectonics and sedimentation interaction across the basin.

Cehel Taghi growth syncline

The Cehel Taghi growth syncline involving Amiran and Kashkan formations shows unambiguous growth strata, unconformities and minor thrusting in the innermost part of the Amiran Basin, north of the Khorramabad anticline. The syncline was mapped in detail and sampled extensively to determine the timing of the deformation in the coupled Cehel Taghi syncline and Hassan Abad anticline (Fig. 9).

The Amiran and Kashkan Formations show a large increase in thickness from the steep NE flank of the growth syncline to the shallow-dipping SW flank. The Amiran conglomerates have a thickness of 300 m on the SW flank and less than 100 m on the NE flank (Fig. 9). Gilbert delta topsets define the NW flank, whereas the SW flank contains an entire Gilbert delta succession, which indicates that the NW flank was originally higher than the SE flank. Continuity between both flanks indicates that the thickening is purely depositional. Above these beds, the poorly exposed Kashkan Formation is almost three times thicker on the SW flank than on the NE flank. Above the Kashkan Formation, the Shahbazan succession was deposited conformably or at low angle to the bedding on the SW flank of the syncline but with a high-angle unconformity on top of the subvertical growth strata of the NE flank, where it truncates the Kashkan Formation and rests on the Amiran Formation (Fig. 9), as observed c. 1 km east of the mapped sector. As we know the topsets of the Amiran Gilbert delta system and the carbonate layers of the Shahbazan Formation to be originally horizontal surfaces, the angular relationships between the Amiran and the Shahbazan Formation and the thickness variations of Kashkan Formation must be related to a folding stage predating the deposition of the Shahbazan Formation. The Cehel Taghi growth syncline was active during the deposition of the Amiran and the Kashkan formations in Campanian and Maastrichtian times, recording the growth of the Hassan Abad anticline to the NE. During this early folding stage, minimum tiltings of c. 65° and c. 7° can be respectively estimated on the NE and SW flanks of the Cehel Taghi syncline. Oligocene Shahbazan limestones that capped the Late Cretaceous growth strata were later folded and thrust during Miocene times after the deposition of the Asmari Formation.
SW flank of the Dariagirveh growth anticline

The Dariagirveh growth anticline is located to the NE of the Rit anticline (Fig. 3). The SW flank of the anticline clearly shows growth strata involving the Amiran–Shahbazan sequence. The Amiran Formation shows a measured decrease in thickness of >200 m between the two flanks of the growth syncline and a differential tilting of c. 40° from base to top (Fig. 10). Above the Amiran Formation, the Taleh Zang and Kashkan formations thin northeastwards below the onlapping Shahbazan Formation (Fig. 10a). In our opinion, these features record continuing syndepositional folding. Correlation with the nearby NE Rit section indicates that the initial growth of the anticline occurred at least from Thanetian (58.7–55.8 Ma) to Eocene (55.8–34 Ma) times, which implies a slow but continuous growth of the Dariagirveh anticline.

Opposing palaeoslopes of the Sultan–Rit growing anticline

The Sultan–Rit anticline early growth is inferred from marked changes in stratigraphic thickness. The Amiran Formation is reduced in thickness by about 100 m (13%) across the anticline southwestwards, whereas the Kashkan Formation thickness in the NE is practically double that in the SW flank (Fig. 4). Divergent directions of palaeoslope outlined by slumps on both limbs of the anticline are in agreement with this early growth. Palaeoflow directions of slumps in the Purple Shales Member of the Pabdeh Formation and the basal layers of the Amiran Formation are to the north and NW on the NE flank of the Sultan–Rit anticline and to the SE on its SW flank (Fig. 11). These divergent palaeoslope directions approximately in the same stratigraphic position suggest the occurrence of a palaeohigh in the current location of the Rit anticline, which we relate to the initial stages of growth of this anticline. This is especially unambiguous for the north-directed slumps observed on the northern limb. The age of these deposits indicates that the growth of the anticline started during deposition of the Amiran Formation in Thanetian times. However, the Taleh Zang clinoforms were able to prograde across the structures, suggesting a relatively limited structural relief at this stage (Figs 6 and 11). The thickness increase of the Kashkan Formation on the SW flank of the anticline indicates its major growth during deposition of red beds at early Eocene times.

The position and age of syndepositional anticlines in the Amiran Basin suggest that deformation migrated southwestwards from latest Campanian in the Cehel Taghi growth syncline to Thanetian–early Eocene in both the Dariagirveh and the Sultan–Rit growth anticlines. The Shahbazan limestones at the Eocene–Oligocene boundary partly fossilize this previous foreland deformation across the entire basin. Thickness variations in the Shahbazan Formation (40 m in the Dar Howz area and c. 170 in the Push-e Jangal–Amiran area) as well as onlapping beds in the Dariagirveh anticline record a palaeorelief predating its deposition, also in agreement with an early folding stage, as will be discussed below.

Discussion

Depositional architecture of the Amiran Basin

Age and thickness constraints are used to construct a NNE–SSW chronostratigraphic panel illustrating the depositional architecture of the Amiran Basin at the time of deposition of the Eocene–Oligocene Shahbazan Formation, which is used as a horizontal marker (Fig. 12a). Constrained time lines correspond to the top Campanian (70.6 Ma), top Maastrichtian (65.5 Ma), top Danian (61.7 Ma), top Selandian (58.7 Ma), top Thanetian (55.8 Ma) and top Ilerdian (52.8 Ma). Once flattened, the architecture of the Amiran Basin resembles a typical foreland basin fill in which the time lines cross the lithostratigraphic boundaries (formations) defining successive aggrading–prograding depositional wedges that become younger towards the foreland (Fig. 12a; e.g. Puigdefabregas & Souquet 1986; Allen et al. 1991; Sinclair & Allen 1992). The accurate age control resulting from this work indicates the isochrony of non-marine Kashkan red beds grading into Taleh Zang small carbonate platforms, subsequently into slope and deep marine Amiran turbidites, and finally to basin-floor Gurpi–Pabdeh marls and shales. This lateral passage can be traced unambiguously from Maastrichtian to Cuisian times. During the filling of the basin coeval shortening produced regional uplift in the inner part (Homke et al. 2009) and folding of the basin fill.

The Amiran Basin is filled by a thick siliciclastic sequence sourced from the Late Cretaceous topographic relief formed as a consequence of the obduction of oceanic slivers on top of the
Arabian margin sedimentary cover succession. These relatively thin oceanic and radiolaritic tectonic slices piled up, possibly causing elevated topography close to the NE margin of the basin. Subsequent erosion of subaerial areas and transport of clastic material by transverse fluvial and alluvial coarse-grained systems is recorded by the Amiran conglomerates and most of the Kashkan succession. In this mostly siliciclastic depositional system, the Taleh Zang marine platforms are limited and discontinuous in space and are interpreted to have developed either in protected intra-lobe areas adjacent to major distributary channels or as transgressive platforms developed during periods of marine transgression overlying deltaic topsets. The oldest outcrops of these platforms, Maastrichtian in age, are thin and isolated. In the central part of the basin, the Taleh Zang platforms are formed by discontinuous reefal build-ups whereas to the SW the platforms are continuous, more clastic and strongly prograding (Fig. 6). This indicates that the basin infill material was still flowing across the basin from NE to SW, in spite of incipient folding.

The middle–late Eocene basin fill is the least constrained by...
our dating data. However, observed geometries and accurate
dating of the Shahbazan Formation base at the Eocene–Oligocene
boundary constrain the depositional scenario. The base of the
Shahbazan Formation is normally paraconformable (transitional
or sharp) with the underlying strata but angularly unconformable
above early growth structures as documented in this study (Figs 9
and 10). These changing geometries suggest a structural control
on the distribution of the Kashkan Formation, with protracted
deposition in the growth synclines and restricted deposition, non-
deposition or erosion on top of active anticlines. These processes
are synchronous with a period of denudation identified by Homke
et al. (2010).

The paraconformable Shahbazan and Asmari formations are
probably separated by a depositional hiatus in western Lurestan
and eastern Khuzestan (James & Wynd 1965, Sherkati et al.
2006), which has been lately dated as late Oligocene–early
Miocene in the Lurestan area (Homke et al. 2009). Determined
ages for the Shahbazan and Asmari formations in the Khorrama-
bad anticline suggest a maximum possible hiatus of 7 Ma.

The depositional architecture described for the Amiran Basin
in this paper provides a more accurate documentation and
understanding of the foreland evolution that differs significantly
from well-established existing charts for the analysed time
interval. It also resolves the lack of data in the inner part of the
Amiran Basin, improving the already published results of Homke
et al. (2009). James & Wynd (1965) showed a classical
stratigraphy with the Amiran Formation as the oldest on top of the
Gurpi marls followed by the younger Taleh Zang and
Kashkan formations. In their reconstruction of the basin archi-
tecture (their fig. 11) they illustrated the lateral passage from the
Amiran and Kashkan formations to the Gurpi marls in a
southwestward direction. Also, they proposed a northeastward
lateral transition from the Kashkan beds to the Taleh Zang
platforms in the central part of the basin. Alavi (2004) presented
for the first time an integrated modern stratigraphy for the
Zagros foreland basin, but ages and thus proposed lateral
passages between the depositional units were not accurately
located. In the study by Homke et al. (2009) the geometry of the
inner part of the basin was based on that of James & Wynd
(1965), with the Kashkan Formation unconformable above older
folded depositional units.

Late Cretaceous to early Eocene evolution of the Amiran Basin

The regional chronostratigraphic panel across the Amiran Basin
is used to illustrate the basin evolution from the Campanian to
the early Eocene (Fig. 12b). The oldest basin depocentre
responds to the Campanian on the NE limb of the Khorrama-
bad anticline, where a minimum thickness of 1100 m was
determined (Fig. 12). During the Maastrichtian the depocentre
migrated c. 17 km. Non-marine deposition started during this
period in the Khorrambad anticline (Fig. 12). Deposition rates
between c. 0.16 and c. 0.04 mm a\(^{-1}\) are estimated in the central
part of the basin, and in the distal parts they remain between c.
0.007 and c. 0.002 mm a\(^{-1}\).

During the Danian, the depocentre migrated 13 km to the SW.
The basin fill was deposited in the depocentre at a rate of c.
0.20 mm a\(^{-1}\), and in the distal domains at c. 0.01 mm a\(^{-1}\) (Fig.
12). During the Selandian the basin depocentre shifted c. 6 km to
the SW. The depositional rate at the depocentre was c. 0.20 mm
a\(^{-1}\), and in the distal areas c. 0.02 mm a\(^{-1}\) (Fig. 12). During the
Thanetian, the system progradation accelerated and the depocen-
tre moved c. 14 km southwestwards and continental deposition
reached the Amiran area. This stage was initially defined in the
depocentre by a deposition rate of c. 0.04 mm a\(^{-1}\), subsequently
increasing to c. 0.25 mm a\(^{-1}\) (Fig. 12). Coevally, the hemipelagic
deposition in the distal part remained at a rate of c. 0.01 mm a\(^{-1}\).

During the Istertian, the basin depocentre moved 22 km to the
SW. The deposition rates remained high in the depocentre (c.
0.14 mm a\(^{-1}\)) and very low in the distal domain (c. 0.01 mm a\(^{-1}\)).
Finally, during the Cuisian the basin depocentre migrated 11 km
and reached the northern limb of the Chenareh anticline (Fig. 12).
In this area, the average deposition rate was c. 0.20 mm a\(^{-1}\), but
sporadically as high as c. 1 mm a\(^{-1}\). At the end of this stage, continental deposition reached the Chenareh area.

The 80 km migration of the depocentre from Campanian to
Eocene times started slowly (2–3 mm a\(^{-1}\) from Campanian time
to the end of Selandian, followed by a twofold acceleration (5–
7 mm a\(^{-1}\) from Thanetian to Istertian time. Finally, depocentre
migration slowed during Cuisian time (3 mm a\(^{-1}\); Fig. 12). At
regional scale, the average depocentre migration rate of c. 5 mm
a\(^{-1}\) is much higher than the rate of 1.45 mm a\(^{-1}\) proposed by
Farzipour-Saein et al. (2009). This is clearly related to the higher
resolution of our dataset.

The Amiran Basin in the context of the Arabia–Eurasia
collision zone

The Amiran Basin chronostratigraphy has been integrated with
two recently published palaeostratigraphical maps for the Arabia–
Eurasia collision ( Barrier & Vrielynck 2008): (1) the Maastrich-
tian–early Palaeocene map at c. 65 Ma, when siliciclastic
deposition in the foreland basin began; (2) the early Eocene map
at c. 52 Ma, when the basin was almost full (Fig. 13).

The onset of intra-oceanic obduction is widely accepted to
have taken place during the Cenomanian–Turonian along the
NE Arabian margin and was characterized by the stacking of
relatively thin tectonic slices of material from both oceanic
domains and distal regions of the Arabian continental margin
(Sengör 1990). These tectonic slices were thrust over shallow-
water carbonate ramps and platforms that defined the edge of the
Arabian margin (Mishrif–Sarvak Formation in Zagros and
Natih Formation in Oman; e.g. Ricou et al. 1977; Braud 1987;
Ravaut et al. 1997). The load of the emplaced tectonic nappes
is interpreted to have produced the flexure of the Arabian
margin and the onset of the deep foreland basin deposition
corresponding to the Shiranish and Gurpi formations in the
Zagros (e.g. James & Wynd 1965; Jassim & Goff 2006),
associated with submarine olistostrome deposition in the internal
parts of the basin (e.g. Braud 1987; Piryaee et al. 2010).
A similar evolution is envisaged in the Oman area, which is
separated from the Zagros by a transform fault (Fig. 13a; e.g.
Alsharhan 1989; Robertson et al. 1990; Warburton et al.
1990).

The Tanjero–Kolosh foreland basin in the Kirkuk embayment
and Kurdistan (Iraq) formed in lateral continuity with the
Amiran Basin in the Lurestan Province (Fig. 13a). The
Tanjero–Kolosh foreland basin was filled during the latest
Cretaceous by the Tanjero Flysch in the NE and by outer shelf-
basinal deposits of the Shiranish Formation in the SE, separated
by the carbonate ramps of the Aqra–Bekhme Formation (James
& Wynd 1965; Jassim & Goff 2006). This basin defines a
>350 km long, 100 km wide trough in front of the current
Imbricated Zone, with sedimentary thicknesses exceeding
2000 m, rapidly decreasing to less than 300 m southwestwards
(Jassim & Buday 2006). The composition, geometry and
thickness of the Maastrichtian–early Palaeocene Amiran and
Tanjero–Kolosh basins suggest the occurrence of elevated topographies towards the NW, providing the required tectonic loads as well as sources of supply to basins (Fig. 13a). Also, the deposition of the carbonate Tarbur Formation in Fars Province (James & Wynd 1965) suggests lower topographies of the obduction complex in this area (Fig. 13a). During this stage of the basin evolution, the deformation front was active and situated along the NE border of the basin, although folding within the basin was incipient. Coevally, in the Oman Mountains expansive carbonate platforms were deposited on top of siliciclastic foreland basin deposits (Glennie et al. 1974), postdating the obduction stage and recording the onset of a long-lasting quiescent period (Warburton et al. 1990).

The early Eocene period corresponds to the final stage of filling of the early foreland basins (Fig. 13b). This period, characterized in the eastern Arabian margin by the extensive deposition of the Pabdeh Formation and equivalent distal deposits (Fig. 13b), corresponds to the study area to the deposition of the Amiran–Taleh Zang–Kashkan system. Syndepositional folding suggests coeval minor tectonic shortening in the hinterland. In the Tanjero–Kolosh basin, the transition from hinterland to foreland of the non-marine Gercus Formation to the carbonate platforms of the Khurmala Formation and the Kolosh Flysch probably corresponds to the same time interval (Fig. 13b; James & Wynd 1965; Jassim & Buday 2006b). The concurrent most distal basin deposition is defined by the Aaliji and Jaddala formations, which are equivalent to the Pabdeh Formation (James & Wynd 1965). Contrasting with the Amiran Basin infill, the early Eocene succession of the Fars area is characterized by the shallow-water and marine–continental transitional facies of the Jahrum and Sachun formations (James & Wynd 1965).

Conclusions
In this paper we have characterized the architecture of the early Amiran Basin by constructing a stratigraphic transect across the basin constrained by 13 field-based stratigraphic logs and more than 350 samples for chronostratigraphy with multiple methods (calcareaeous nannoplankton, large foraminifera, strontium isotope dating ($^{87}$Sr/$^{86}$Sr) and palynology). The stratigraphic transect forms the basis for backstripping analysis to determine the foreland basin evolution in terms of subsidence, progradation and early folding.

The depositional architecture of the basin is characterized by a diachronous, shallowing upwards, and mixed clastic–carbonate succession deposited from Late Cretaceous to early Eocene time. The precise age control obtained in this study provides multiple time lines indicating the isochrony of non-marine Kashkan red beds grading into limited carbonate Taleh Zang platforms, subsequently into slope–deep marine Amiran turbidites and finally to basin-floor Gurpi–Pabdeh marls and shales. This passage can be correlated unambiguously from Campanian times in the inner segments of the basin to Ypresian times in the outer parts. Significant lateral thickness variations, of both the lithostratigraphic units and the isochronous deposits, are also a typical feature of the Amiran Basin, with a maximum thickness of 1.5 km in its central part. These variations are intimately related to the interaction between tectonics and sedimentation, and record the diachronicity of the early folding stage across the basin. The earliest evidence for fold growth observed in the Amiran Basin is found on the northern limb of the Khorramabad anticline, indicating at least a Maastrichtian age for the initiation of this fold. In the Sultan–Rit anticline, evidence of Thanetian–Ypresian syntectonic deposition has also been observed, suggesting a southwestward migration of the deformation.

The Amiran Basin evolution started at least during the Campanian (83.5–70.6 Ma) with the deposition of the Amiran Formation along the NE side of the Khorramabad anticline. During the early–middle Palaeocene (65.5–58.7 Ma) sedimentation was localized in the northern part of the basin, with slow progradation rates (c. 2.4 mm a$^{-1}$) and a subsidence rate of c. 0.28 mm a$^{-1}$. Subsequently, during the late Palaeocene–earliest Eocene (58.7–52.8 Ma) the southwestwards progradation of the depositional system increased to c. 6 mm a$^{-1}$, and then decreased...
again to c. 3 mm a⁻¹ during Cuisian time (48.6–34 Ma). During this last period, initial depocentre subsidence rates remained stable at c. 0.27 mm a⁻¹ and subsequently decreased to c. 0.16 mm a⁻¹. Finally, the middle Eocene–Oligocene stage was defined by an overall decrease of the sedimentation rate and the Oligocene–Miocene (34–19 Ma) was defined by at least two subsidence pulses, as recorded by the transgressive Shalbazar and Asmari formations.

This study is a contribution of the Group of Dynamics of the Lithosphere (GDL) within the framework of a collaborative project with the Statoil Research Centre in Bergen (Norway). We thank both Statoil and the National Iranian Oil Company (NIOC) for support in the field as well as for permission to publish these results. Additional support was provided by MCI project CGL 2008-00809. We thank H. Emami, V. Hasani, P. Rafaei and M. Fallah for field assistance. We are also grateful to J. M. McArthur for providing the latest version of the statistical LOWES for 87Sr/86Sr stratigraphic dating. This paper also benefited from the comments of T. Needham and two anonymous reviewers.

References

Agard, P., Omrani, J., Jolivet, J. & Mouthereau, F. 2005. Convergence history across Zagros (Iran): constraints from collisional and earlier deformation. Geologische Rundschau, 94, 401–419.
Alavi, M. 1994. Tectonics of the Zagros orogenic belt of Iran: new data and interpretations. Tectonophysics, 229, 211–238.
Alavi, M. 2004. Regional stratigraphy of the Zagros fold–thrust belt of Iran and its proforeland evolution. American Journal of Science, 304, 1–20.
Allen, P.A., Crampton, S.L. & Sinclair, H.D. 1991. The inception and early evolution of the North Alpine Foreland Basin, Switzerland. Basin Research, 3, 143–163.
Alsharhan, A.S. 1989. Petroleum geology of the United Arab Emirates. AAPG Bulletin, 73, 947–959, doi:10.1144/0016-76492008-138.
Bown, P.R. 2005. Convergence history of the proto-Zagros foreland basin, Lurestan Province, SW Iran. Geological Society of America Bulletin, 121, 963–978, doi:10.1130/B26035.2603.
Bown, P.R., Verge’s, 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, 391–407.
Bown, P.R., Verge’s, J., et al. 2009. Late Cretaceous–Paleocene formation of the proto-Zagros foreland basin, Lurestan Province, SW Iran. Geological Society of America Bulletin, 121, 963–978, doi:10.1130/B26035.2603.
Bown, P.R., Verge’s, J., et al. 2010. Insights in the exhumation history of NW Zagros from bedrock and detrital apatite fission-track analysis: evidences for a long-lived orogeny. Basin Research, 22, 659–680.
James, G.A. & Wynd, J.G. 1965. Stratigraphic nomenclature of Iranian Oil Consortium Agreement Area. AAPG Bulletin, 49, 2182–2245.
Jassim, S.Z. & Buda, T. 2006. Late Turonian–Danian megasequence AP9. In: Jassim, S.Z. & Goff, J.C. (eds) Geology of Iraq. Dolin, Prague; Moravian Museum, Brno, 141–154.
Jassim, S.Z. & Buda, T. 2006b. Middle Palaeocene–Eocene Megasequence (AP10). In: Jassim, S.Z. & Goff, J.C. (eds) Geology of Iraq. Dolin, Prague; Moravian Museum, Brno, 155–168.
Jassim, S.Z. & Goff, J.C. (eds) 2006. Geology of Iraq. Dolin, Prague; Moravian Museum, Brno.
Khadi, S., Mouthereau, F., et al. 2009. Magnetochronology of synorogenic Miocene foreland sediments in the Fars arc of the Zagros Folded Belt (SW Iran). Basin Research, 21, 918–932.
McQuarrie, N., Stock, J.M., Verdel, C. & Wernicke, B.P. 2003. Cenozoic evolution of Neotethys and implications for the causes of plate motions. Geophysical Research Letters, 30, 2036, doi:10.1029/2003GL017992, 012003.
Piryaæi, A., Reimder, J.J.G., van Buchem, F.S.P., Yazdi-Moghadam, M., Sadowski, J. & Danelian, T. 2010. The influence of Late Cretaceous tectonic processes on sedimentation patterns along the northeastern Arabian plate margin (Fars province, SW Iran). In: Leturmy, P. & Robin, C. (eds) Tectonic and Stratigraphic Evolution of Zagros and Makran during the Mesozoic–Cenozoic, Geological Society, London, Special Publications, 330, 211–251.
Quigdefaregacs, C. & Souquet, P. 1986. Tecto-sedimentary cycles and depositional sequences of the Mesozoic and Tertiary from the Pyrenees. Tectonophysics, 129, 173–203.
Ravaut, P., Baut, R., Hassan, R., Rousset, D. & Al Yahya’ey, A. 1997. Structure and evolution of the northern Oman margin: gravity and seismic constraints over the Zagros–Makran–Oman collision zone. Tectonophysics, 279, 253–280.
Ricou, L. 1971. Le periarabian ophiolite crossant. A belt of thrusts emplaced during Late Cretaceous. Revue de géographie physique et de géologie dynamique, 13, 327–335 [in French].
Ricou, L.E., Braud, J. & Brunn, J.H. (eds) 1977. The Zagros, memoirs of A.F. Lapparent (1905–1975): Mémoire hors Série de la Société Géologique de France, Paris, Société Géologique de France, 8, 33–52.
Robertson, A.H.F., Seable, M.P. & Ria, A.C. (eds) 1990. The Geology and
Tectonics of the Oman Region. Geological Society, London, Special Publications, 49.

Sella, G.F., Dixon, T.H. & Mao, A. 2002. REVEL: A model for recent plate velocities from space geodesy. Journal of Geophysical Research B: Solid Earth, 107, 2081–2111.

Sengör, A.M.C. 1990. A new model for the late Palaeozoic–Mesozoic tectonic evolution of Iran and implications for Oman. In: Robertson, A.H.F., Searle, M.P. & Morton, A.C. (eds) The Geology and Tectonics of the Oman Region. Geological Society, London, Special Publications, 49, 797–831.

Sengör, A.M.C., Cin, A., Rowley, D.B. & Nie, S.Y. 1993. Space–time patterns of magmatism along the Tethysides: a preliminary study. Journal of Geology, 101, 51–84.

Sepehr, M. & Cosgrove, J.W. 2005. Role of the Kazerun Fault Zone in the formation and deformation of the Zagros Fold–Thrust Belt, Iran. Tectonics, 24, TC5005, doi:10.1029/2004TC001725.

Sherkati, S., Molinaro, M., Frizon de Lamotte, D. & Letouzey, J. 2005. Detachment folding in the Central and Eastern Zagros fold-belt (Iran): salt mobility, multiple detachments and late basement control. Journal of Structural Geology, 27, 1680–1696, doi:10.1016/j.jsg.2005.1605.1010.

Sherkati, S., Letouzey, J. & Frizon de Lamotte, D. 2006. Central Zagros fold–thrust belt (Iran): New insights from seismic data, field observation and sandbox modeling. Tectonics, 25, doi:10.1029/2004TC001766, 002006.

Sinclair, H.D. & Allen, P.A. 1992. Vertical versus horizontal motions in the Alpine orogenic wedge: stratigraphic response in the foreland basin. Basin Research, 4, 215–232.

Sinclair, H.D., Coakley, B.J., Allen, P.A. & Watts, A.B. 1991. Simulation of foreland basin stratigraphy using a diffusion model of mountain belt uplift and erosion: An example from the central Alps, Switzerland. Tectonics, 10, 599–620.

Stoneley, R. 1981. The geology of the Kuh-e Dalneshim area of southern Iran, and its bearing on the evolution of southern Tethys. Journal of the Geological Society, London, 138, 509–526.

Vergès, J., Marzo, M., Santaeularia, T., Serra-Kiel, J., Burbank, D.W., Múnoz, J.A. & Gimenez-Montsant, J. 1998. Quantified vertical motions and tectonic evolution of the SE Pyrenean foreland basin. In: Fleet, A.J., Morton, A.C. & Roberts, A.M. (eds) Cenozoic Foreland Basins of Western Europe. Geological Society, London, Special Publications, 134, 107–134.

Vergès, J., Karpuz, R., Efstathou, J., Goodarzi, M.H., Emami, H. & Gillespie, P. 2010. Multiple detachment folding in Pusht-e Kuh arc, Zagros. Role of mechanical stratigraphy. In: McClay, K., Shaw, J. & Suppe, J. (eds) Thrust Fault Related Folding. AAPG Memoirs, 94, 1–26.

Warburton, J., Burnhill, T.J., Graham, R.H. & Isaac, K.P. 1990. The evolution of the Oman Mountains Foreland Basin. In: Robertson, A.H.F., Searle, M.P. & Morton, A.C. (eds) The Geology and Tectonics of the Oman Region. Geological Society, London, Special Publications, 49, 419–427.