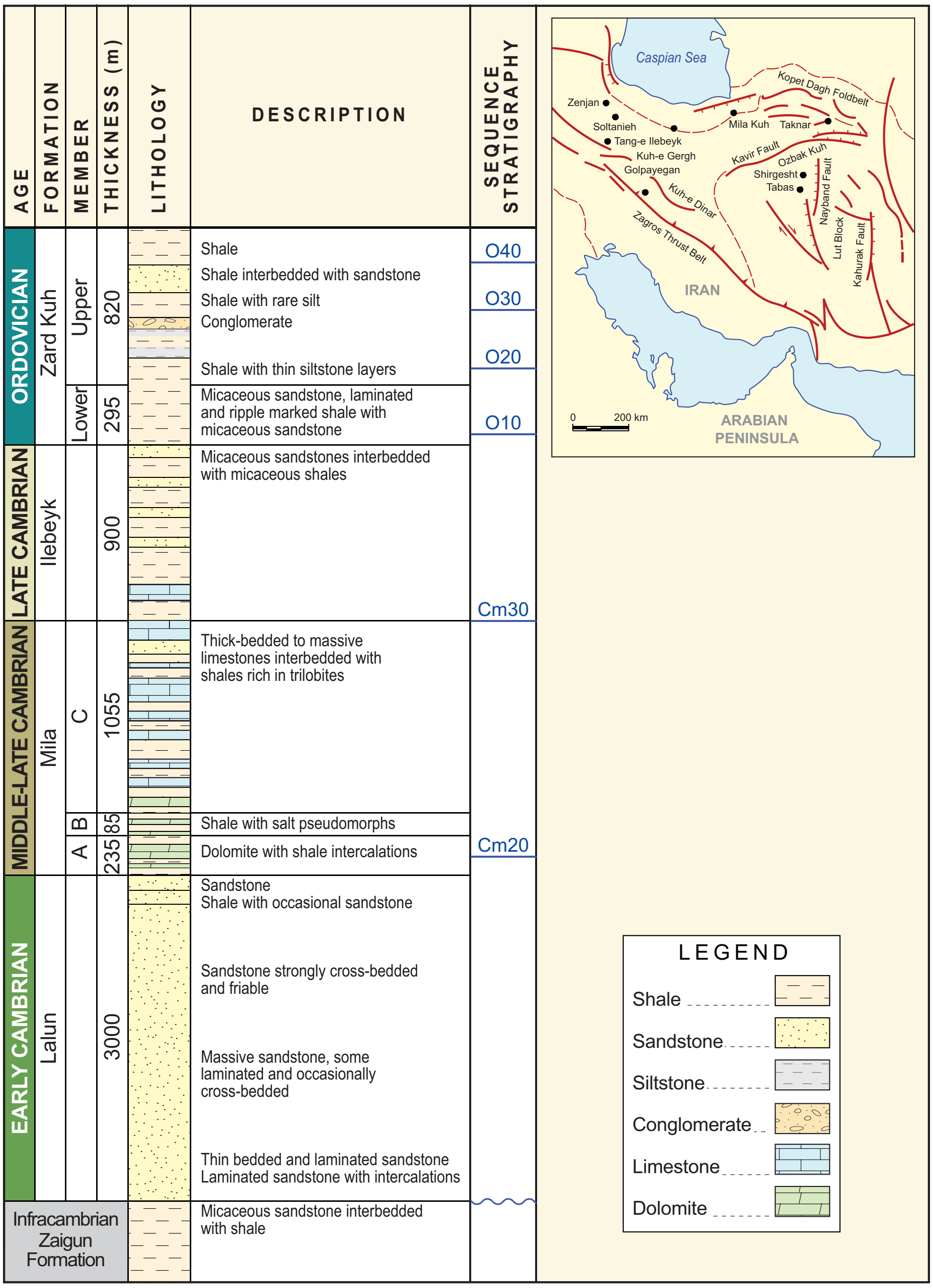

Fig. 4.10. Composite Lower Palaeozoic stratigraphy of Iran. After Setudehnia, 1975; flooding surfaces after Sharland *et al.*, 2001.

2008a) (Fig. 4.8). The formation also occurs in Syria, for example as the basal 13 m of the section penetrated at the *Khanasser-1* well (Best *et al.*, 1993; Barazangi *et al.*, 1993). Equivalent units in Iran are the Zaigun and Lalun Formations (Fig. 4.10) (Davoudzadeh *et al.*, 1986).

Mid-Cambrian marine transgression across the northern part of the Arabian Plate (Konert *et al.*, 2001) led to widespread deposition of a limestone unit (Fig. 4.12) within the otherwise siliciclastic-dominated Cambro-Ordovician succession. This unit is known as the Burj Formation in Jordan (Andrews *et al.*, 1991) (Fig. 4.13; Plate 4.4) and also in Syria, where it is 225 m thick at well *Khanasser-1* (Best *et al.*, 1993). In Turkey, it is referred to as the Koruk Formation (Janvier *et al.*, 1984; Dean *et al.*, 1997) (Figs. 4.8, 4.9). In Iran, the carbonates are assigned to the Mila Formation (Setudehnia, 1975; Ghavidel-Syooki, 1997) (Fig. 4.10). There is a strong velocity contrast between these carbonates and the over- and underlying siliciclastics; the carbonate unit thus forms a seismic marker (e.g. in Syria: Best *et al.*, 1993). A similar reflector has been recognised in seismic sections from the Western Desert in Iraq (e.g. Al-Haba *et al.*, 1994) and can be tied to the Burj Formation in the *Risha-2* well, Jordan (Jassim, 2006c). The carbonates may be very thin or absent in the Southwestern Desert of Iraq. Similarly, in Jordan and western Iraq, the formation thins southwards from about 200 m in the Risha/Rutbah area to 60 m in the southern part of Wadi Sirhan (Andrews *et al.*, 1991; Jassim, 2006c). Further south, the facies pass into marine siliciclastics

Fig. 4.11. Map of Iraq showing the thickness of Megasequence AP2. Interpretation is based mainly on gravity-magnetic data with very little well or outcrop control. Simplified after Jassim, 2006c.

Plate 4.2. Dashed white line indicates onlap of pebbly sandstones of the Lower Cambrian Salib Formation (basal AP2) and other Lower Palaeozoic rocks onto peneplaned Precambrian basement. Location: near Aqaba, southern Jordan, at the road junction with Wadi Rum. Photo by A. Aqrawi.

Plate 4.3 (above). Pebbly arkosic sandstones of the Lower Cambrian Salib Formation at Wadi Numaira, Dead Sea — Aqaba road, southern Jordan. Photo by A. Aqrawi.

within the continental deposits of the Abu Khusheiba Formation (Powell, 1989). In Saudi Arabia, these coastal siliciclastics are recorded as the "spoor" zone of the Saq Formation with *Skolithos* (Powers *et al.*, 1966; Helal, 1968; Al-Laboun, 1986; McGillivray and Husseini, 1992). They onlap the margins of areas uplifted during the Amar collision.

The carbonates comprise tidal flat to lagoonal and occasional oolitic shoal facies (Powell, 1989; Andrews *et al.*, 1991) (see Plate 4.12, page 83). In SE Turkey (and probably also in northern Iraq), the Koruk carbonates are succeeded diachronously by deep-water facies of the Sosink/Seydisehir Formations (Figs 4.8, 4.9). The carbonate shelf was drowned in early Middle Cambrian time in the Amanos Mountains, and in the latest Middle Cambrian in the Zap Valley in SE Turkey (Dean *et al.*, 1997) (Fig. 4.8). The thickness of the carbonates thus increases from 100 m in the Amanos region, to 240 m in the Mardin area, to over 400 m at Hakkari close to the Iraqi border (Cater and Tunbridge, 1992; Dean *et al.*, 1997).

Jassim (2006c) suggested that the Burj/Koruk Formation is approximately 400 m thick in northern Iraq and 200 m thick in the Western Desert. However, he proposed that the Cambrian is absent in Central and Southern Iraq due to onlap over the uplifted Rayn anticlines of the Ar Rayn and Eastern Arabian terranes. It is absent from the Burgan High in Kuwait (based on data in Khan, 1989) (Fig. 4.12).

Siliciclastic-dominated deposition was re-established in the Late Cambrian, with the fluvial sandstones of the Umm Ishrin/Ajram Formations in Jordan (Powell, 1989; Andrews *et al.*, 1991; Makhlouf and Abed, 1991; Amireh *et al.* 1994; Beydoun *et al.*, 1994) (Figs 4.3, 4.5), the Quweira

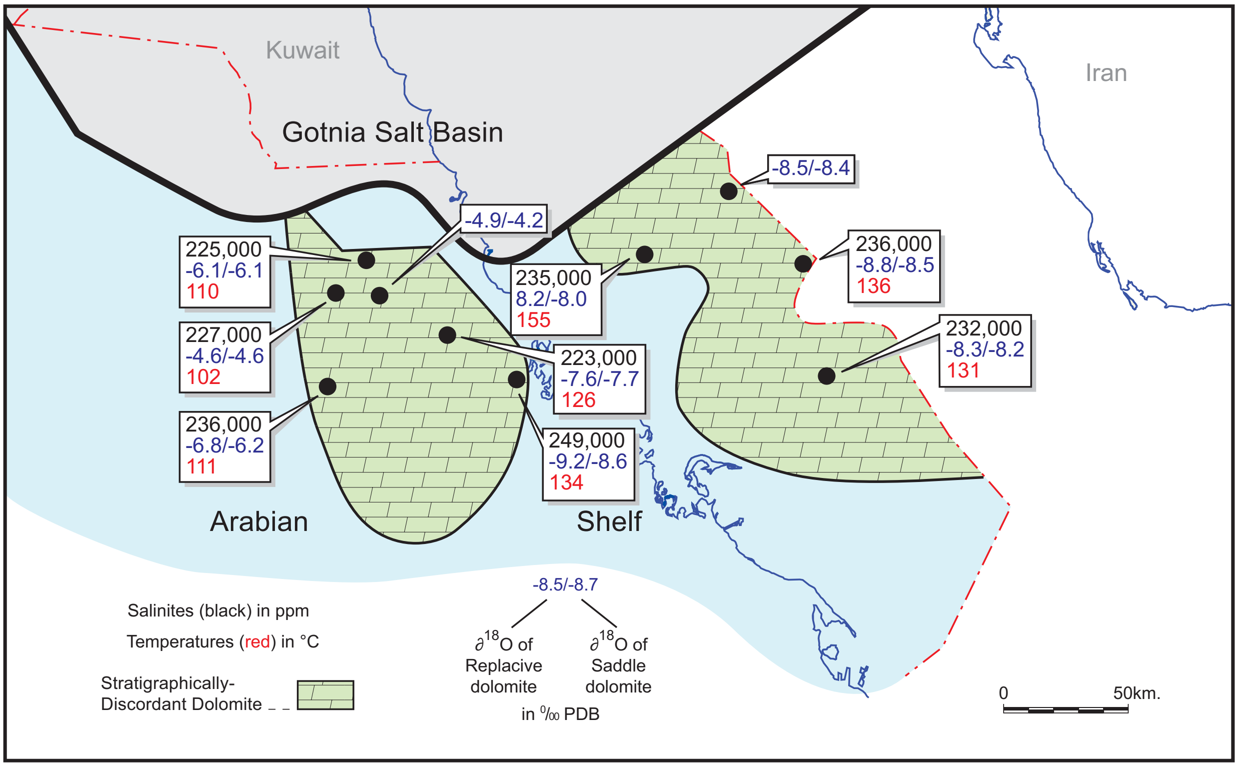

Fig. 6.10. Distribution of stratigraphically discordant dolomite bodies in northern Saudi Arabia, together with temperature and salinity data from fluid inclusion studies. After Broomhall and Allan, 1987.

over a wide area. Two regional-scale "dolomite plumes" have been identified: the first on the border between Saudi Arabia and Kuwait, and the second offshore Saudi Arabia (Fig. 6.10).

This stratigraphically discordant dolomite is locally associated with breccias due to dissolution of the Hith and Arab Formation anhydrites. Dolomite is present in the Tuwaiq Mountain, Hanifa, Jubaila, Arab, Hith and Sulaiy Formations (Fig. 6.11). It is best-developed in the Hanifa Formation. The dolomite shows enhanced porosities and permeabilities compared to host limestones (Broomhall and Allan, 1987).

Fluid inclusion data from the dolomites indicate that precipitating fluids were both hot (temperatures between 102 and 155°C) and saline (at least six times seawater salinity — values of 225,000 to 249,000 ppm NaCl equivalent were recorded) (Fig. 6.10) (Broomhall and Allen, 1987). Both replacive and saddle dolomites are present. They show similar oxygen isotope ratios suggesting that they were derived from the same parent fluid, although the western salient dolomites have a lower temperature, more positive $\delta^{18}O$ signature suggesting that they were precipitated slightly earlier and at shallower depths. Fluid inclusions indicate that oil migration took place at the same time as dolomitisation. There is abundant evidence of dead heavy oil in the pore systems. This may be due to failure of seal integrity due to dolomitisation (Broomhall and Allan, 1987).

Stratigraphically concordant non- fabric-preserving dolomites and stratigraphically-discordant baroque dolomite also occur in the Arab-D carbonate reservoir in the *Ghawar* field, some 500 km to the south of the Gotnia Basin. These dolomites precipitated at temperatures of 85–114°C from pore waters with a salinity of 195,000 – 230,000 ppm NaCl equivalent (Cantrell *et al.*, 2004). Stratigraphically discordant dolomitisation of Middle Jurasic rocks has also been reported to occur in Lebanon, where it is attributed to penecontemporaneous igneous activity (Nader and Swennen, 2004).

The dolomitisation of Middle Jurassic carbonates, and also perhaps of overlying intervals (in the Qamchuqa and Shiranish Formations and the Asmari/Kirkuk Group) thus appears to be largely hydrothermal in character (e.g. Al-Aasm *et al.*, 2009). The movement of dolomitising fluids may have been associated with the onset of Late Neogene compression in the Gotnia Basin, which caused rupturing of Jurassic and deeper evaporite seals and therefore permitted the large-scale mobilization of overpressured Mg-rich formation waters. Broomhall and Allan (1987) interpreted the dolomites to have been formed by brines migrating from the Gotnia Basin as a result of burial.

Naokelekan Formation

The Naokelekan Formation was first described from outcrops in NE Iraqi Kurdistan. It is a highly condensed formation, 9 to 34 m thick (typically less

Plate 6.8. Field photographs of the Upper Jurassic Surmeh Formation at the Mungasht anticline on the eastern margin of the Gotnia Basin in the Iranian Zagros. Bituminous dolomite units are dark brown in the field and contrast with the intercalated pale grey, tightly cemented limestone units. Bitumen-filled vugs (bottom right) are frequently 5-10 cm in diameter. Photos by J. Goff.

than 20 m). The formation can be divided into three units at its type locality (see Fig. 6.3 for location) (Dunnington *et al*., 1959):

(i) an upper 3 m of laminated argillaceous limestones;

(ii) a middle 4 m of "Mottled Limestone Beds", comprising hard, calcite-veined limestones which contain ammonites indicating a "probable early Kimmeridgian" age (Dunnington *et al*., 1959);

(iii) a lower 7 m, referred to as the "Coal Horizon", which comprises thin-bedded bituminous limestones and dolomites with beds of bituminous calcareous shale. The unit has slump structures and weathers into nodular "phacoids". Its top is dated as late Oxfordian on the basis of possible identifications of the ammonite *Reineckia* at Naokelekan in Iraqi Kurdistan; the nearby occurrence of *Choffatia* at Kurrek suggests a Callovian age for its base (Dunnington *et al*., 1959).

The formation conformably overlies the Sargelu Formation (Jassim and Buday, 2006d); the upper contact with the Barsarin Formation is often marked by a ferruginous horizon, e.g. in the north Thrust Zone (Hamza and Isaac, 1971, *in* Jassim and Buday, 2006d). Kaddouri (1986) noted a 1.4 m thick pisolitic limestone at this horizon.

The Naokelekan Formation contains a mainly deepwater fauna (Dunnington *et al*., 1959). Buday and Suk (1978) *in* Kaddouri (1986) and Jassim and Buday (2006d), noted that at Halabja and elsewhere in Sulaimaniya Province in Iraqi Kurdistan, deeper-water fauna are present including *Protoglobigerina* sp., *Cadosina* sp. and the Callovian–Oxfordian belemnite *Hibolites semihastatus*. Shallower-water microfossils also occur such as *Kurnubia palastinensis* Henson, *Ammobaculites* sp., Textularidae sp., *Nautiloculina oolithica*, and the algae *Cladocoropsis*, *Thaumatoporella* sp. and *Cayeuxia doerflesiana*. Indeterminate dascycladaceans together with the stromatoporoid *Shuqraia "heybroeki"* (now *zuffardi*) also occur, indicating a Callovian–Kimmeridgian age (Buday and Suk, 1978, *in* Kaddouri, 1986).

Basinal Najmah Formation

An equivalent of the Naokelekan Formation is the informally-defined "basinal Najmah Formation" in wells in central and southern Iraq and also in Kuwait. This unit includes basinal organic-rich limestones with shelf and slope carbonates (Goff, 2005). Other examples of the "basinal Najmah Formation" occur between Awasil and Makhul,

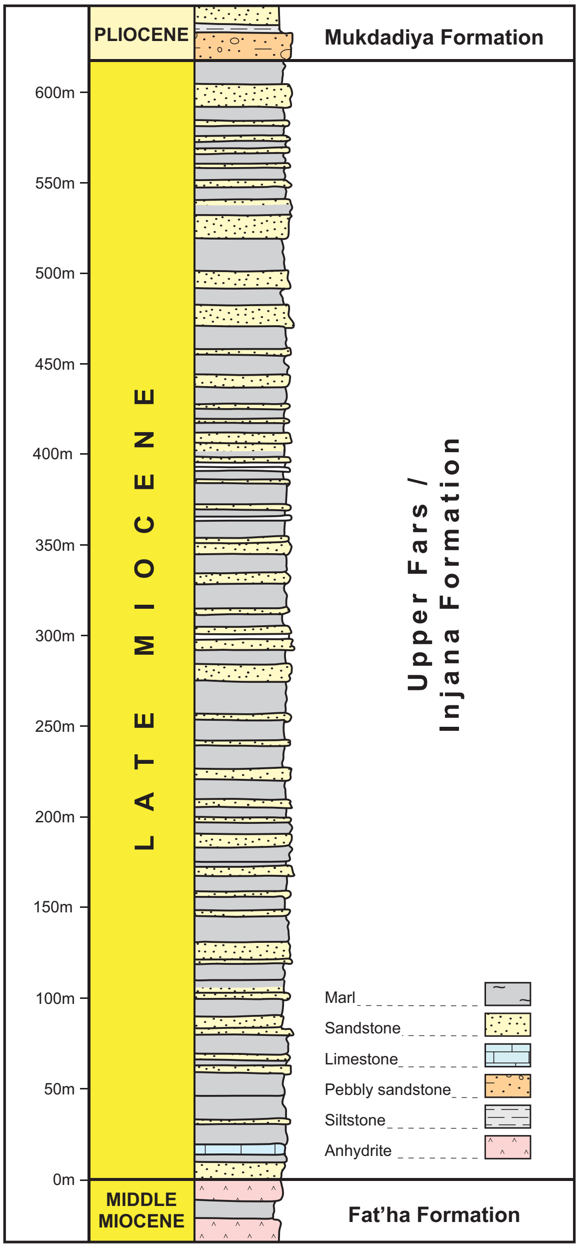

Fig. 8.34. Stratigraphic column for the Upper Fars (Injana) Formation at its type locality at Jebel Hamrin. After Al-Rawi *et al.*, 1992.

reported from the Jeribe Limestone underlying the Lower Fars by Prazak (1978).

Upper Fars Formation

This formation comprises varicoloured marls and siltstones with beds of sandstones and grits. Occasional beds of freshwater limestones (with ostracods and charophytes), lacustrine clays and bentonites also occur (Plate 8.30). The formation is typically 600 to 800 m thick (Fig. 8.34) and forms "badlands" topography (Plate 8.31). Buday (1980) and Al-Rawi *et al* (1992) reported that the formation reaches 2000 m in thickness but this may be an overestimate because of probable inclusion of the overlying Lower Bakhtiari Formation where this is composed mostly of mudstones.

Plate 8.30. Middle-Upper Fars Formation. Lacustrine clays, limestones and bentonite. Injana, Jebel Hamrin South. Photo by M. Tucker.

Plate 8.31. Upper Fars Formation "badlands" topography, Injana, Jebel Hamrin South. View from a gypsum ridge at the top of the Lower Fars. Photo by M. Tucker.

Plate 8.32. Conglomerates and sandstones of the Lower Bakhtiari Formation cropping out in the Khanzad hills, about 15 km north of Erbil, Iraqi Kurdistan. Photo by A. Aqrawi.

Al-Rawi *et al.* (1992) renamed the Upper Fars Formation the Injana Formation, and defined a type locality at Injana along the main Baghdad–Kirkuk road on the NE limb of Jebel Hamrin South (Plate 8.31). A supplementary type section occurs in well *Gilabat-1* (Al-Rawi *et al.*, 1992). The formation is 620 m thick at Injana and consists of alternating red, brown and grey marls, siltstones, and sandstones with seams of gypsum; fossils include gastropods and bivalves. In the Jambur and

Makhul-Khanuqah areas, rare freshwater limestones containing ostracods and charophytes occur. An oyster limestone was recorded 60 m above the base of the formation at Jebel Pulkhana (Al-Naquib, 1960).

The formation is assumed to be of early late Miocene age based on its stratigraphic position below the uppermost Miocene Lower Bakhtiari Formation. It is interpreted here to have been deposited in an estuarine to lacustrine environment.

Lower Bakhtiari Formation

This formation (Plate 8.32) was deposited synchronously with the growth of major anticlines and thus varies in thickness and facies. It was originally included in the "Kurd Series" by Pascoe (1922) but was later reassigned to the Lower Bakhtiari Formation in the Tertiary part of the *Iraq Lexicon* (van Bellen, 1959). Al-Rawi *et al.* (1992) renamed the Lower Bakhtiari Formation the Mukdadiya Formation, whose type section (Fig. 8.35) is on the NE flank of Jebel Hamrin. Here, the formation is 1411 m thick here and comprises sandstones, pebbly sandstones, grey mudstones and siltstones with stacked "fining up cycles".

Thickness

Dunnington (1958) published an isopach map of northern Iraq (Fig.8.36) for the combined Upper Fars and Bakhtiari Formations using estimated thicknesses for synclinal areas. He noted that the major anticlines grew during deposition of the Bakhtiari and considered that "*a true isopach should reveal closures of attenuation over every rising structure but that unfortunately the information which would be required for such a map is not accessible*". He noted that it is difficult to estimate the thickness of the Bakhtiari Formation because thickness measurements can be made only on the flanks of anticlines "*where depositional and some erosional attenuation is known to have occurred*".

His final isopach map (Dunnington, 1968) was created after "arbitrary elimination of crestal attenuation". He emphasised the shallowing of the basin to the NW so that "*the synclinal thicknesses in the vicinity of the NW plunge of Kirkuk were only of the order of 5000 ft (1525m)*". He noted that the original thickness of the "Passive Group" comprising all units above the middle part of the Lower Fars was between 6000 and 13,000 ft (1830-3960 m) prior to rapid late Pliocene – early Pleistocene uplift and erosion. The maximum recorded thickness of the Lower Bakhtiari Formation in Iraq is 2050 m (van Bellen *et al.*,1959) although the location of this section was not given.

On the NE flank of the Kirkuk anticline, Pascoe (1922) noted that the thickness of the Lower Stage Kurd Series (equivalent to the Upper Fars and Lower Bakhtiari) exceeds 7000 ft (2000 m), and that the thickness of the combined Lower and Upper Bakhtiari Series "must exceed 12,000 ft (3500 m)".

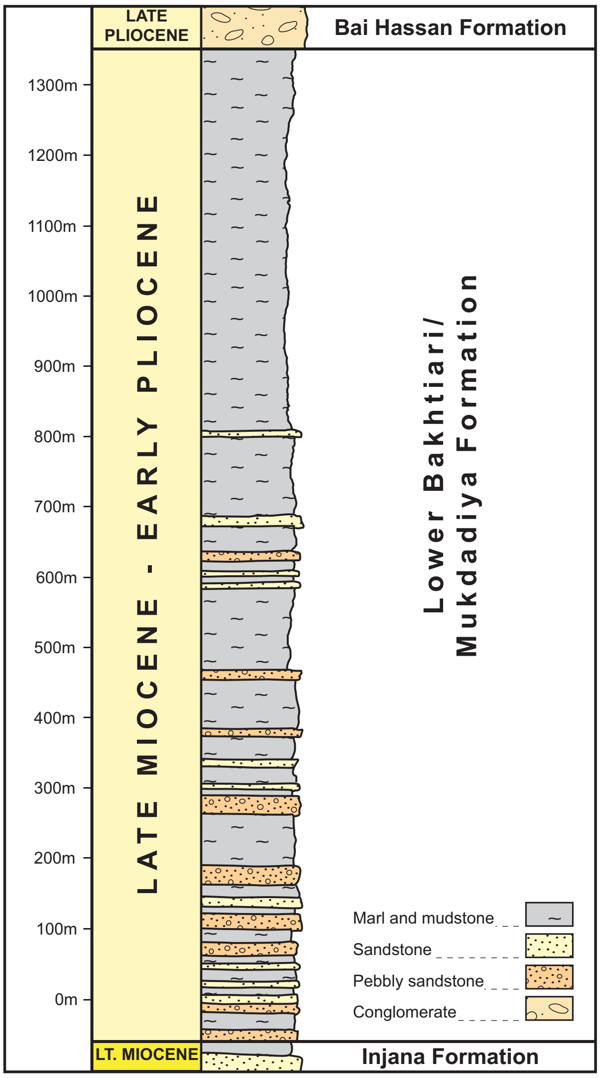

Fig. 8.35. Stratigraphic column for the Lower Bakhtiari (Mukdadiya) Formation at its type locality at Jebel Hamrin. After Al-Rawi *et al.*, 1992.

Stratigraphy

Pascoe (1922) informally recognised five units in the "Kurd Series" in the Kifri area. The lower unit (Lower Stage Unit: a) can be correlated with the Upper Fars Formation. The succeeding units (b) and (c) in the Lower Stage correspond to the Lower Bakhtiari Formation.

In unit (b), Pascoe (1922) recorded the presence of thick, massive sandstone beds which were relatively soft, friable and frequently current bedded, and sometimes full of "root-like concretions". He noted that the sandstone intervals increase in thickness upwards in the middle of the unit, and that the sandstones become pebbly in the same direction and contain thin conglomerates. He observed that the unit "*produces topography consisting of ridge after ridge rapidly alternating with deep, narrow, straight, simple valleys*".