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REGIONAL STRATIGRAPHY OF THE ZAGROS FOLD-THRUST BELT OF IRAN AND ITS PROFORELAND EVOLUTION

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ABSTRACT. The latest Neoproterozoic through Phanerozoic stratigraphy of the Zagros fold-thrust belt of Iran has been revised in the light of recent investigations. The revised stratigraphy consists of four groups of rocks, each composed of a number of unconformity-bounded megasequences representing various tectonosedimentary settings. In the lowest group, ranging in age from latest Precambrian to Devonian(?), the uppermost Neoproterozoic to middle Cambrian rocks constitute a megasequence of evaporites, siliciclastic deposits, and interlayered carbonates, which were deposited in pull-apart basins that developed by the Najd strike-slip fault system. This megasequence is overlain by a second one, Middle to Late Cambrian in age, which consists of shallow, marine siliciclastic and carbonate rocks representing deposition in an epicontinental platform. The overlying shales, siltstones, and partly volcanogenic sandstones of Ordovician, Silurian, and Devonian(?) age are local remnants of stratigraphic units that were extensively eroded during development of several major unconformities. The second group consists of two megasequences, one Permian and the other Triassic, composed of widespread, transgressive basal siliciclastic rocks and overlying evaporitic carbonates of an equatorial, epi-Pangean, very shallow platformal sea. The third group is composed of four megasequences formed of shallow- and deep-water carbonates with some siliciclastic and evaporite deposits, which accumulated on a Neo-Tethyan continental shelf during earliest Jurassic through late Turonian time. The fourth group comprises siliciclastic and carbonate deposits of a largely underfilled, NW- to SE-trending, forward and backward migrating, late Cretaceous to Recent proforeland basin, which has evolved as an integral part of the Zagros orogen. This last group consists of three megasequences (IX, X, and XI) with distinctive lateral and vertical facies variations, which reflect specific tectonic events. Megasequence IX comprises uppermost Turonian to middle Maastrichtian prograding and retrograding siliciclastic and carbonate deposits, whose accumulations reflect emplacement ("obduction") of ophiolite slivers and subsequent collisional events in the Zagros orogen. Megasequence X consists of uppermost Maastrichtian to upper Eocene siliciclastic and carbonate rocks, which deposited first progradationally in front of the Zagros orogenic wedge with reduced contractional tectonic activity, and then retrogradationally due to intensified thrust stacking in the interior parts of the orogen. Megasequence XI consists of Oligocene and lower Miocene carbonate strata deposited retrogradationally shortly after a period of intensified late Eocene thrust faulting in the deformational wedge, and an overlying succession of upward-coarsening, northeasterly-derived siliciclastic deposits of lower Miocene to Recent age which are composed of erosional byproducts of the southwest-vergent Zagros thrust sheets.

INTRODUCTION

The Zagros fold-thrust belt (fig. 1), which extends for about 2000 kilometers from southeastern Turkey through northern Syria and Iraq to western and southern Iran, with its numerous supergiant hydrocarbon fields, is the most resource-prolific fold-thrust belt of the world. This fold and thrust belt is a result of the structural deformation of the Zagros (peripheral) proforeland system, whose present-day expres-

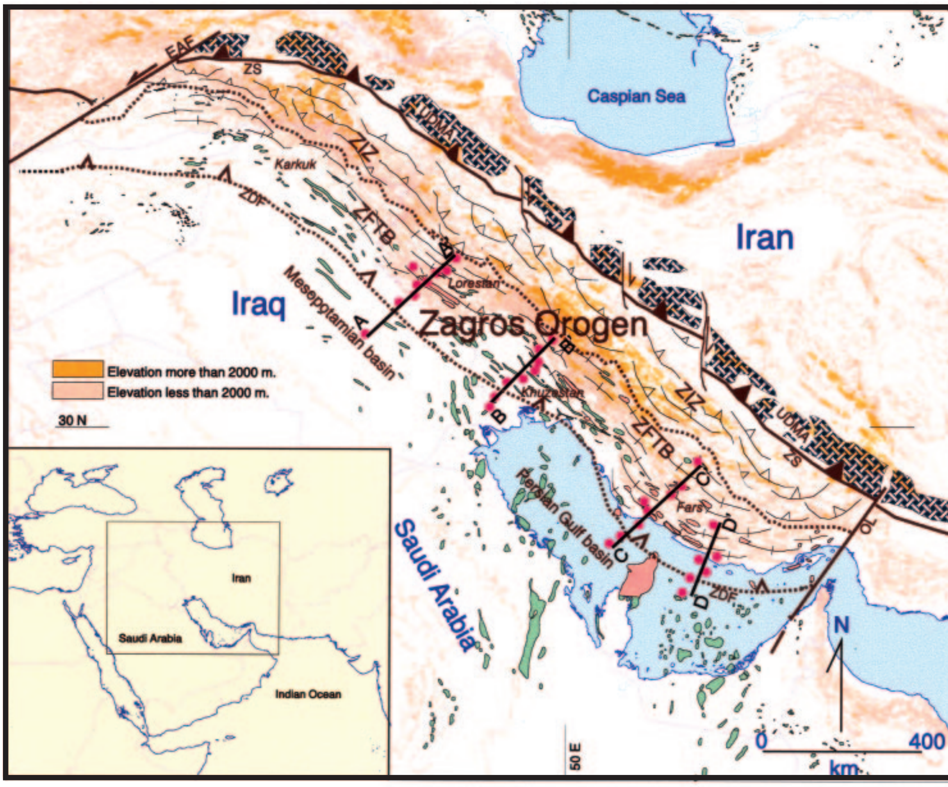

Fig. 1. The Zagros orogenic belt and its subdivisions. Abbreviations: EAF – East Anatolian fault; OL – Oman line; UDMA – Urumieh–Dokhtar magmatic arc; ZDF – Zagros deformational front; ZFTB – Zagros fold-thrust belt; ZIZ – Zagros imbricate zone; ZS – Zagros suture. The locations of the four stratigraphic profiles of figure 3 are indicated. Red dots show locations of the stratigraphic columns. Hydrocarbon fields of the region (oil in green and gas in pink) are also shown.

sion is the marine Persian Gulf and continental Mesopotamia basins (Lees and Falcon, 1952; Purser, 1973; Kassler, 1973; Baltzer and Purser, 1990), and underlying pre-proforeland, mostly platformal and continental shelf deposits. The belt has structurally evolved as a prism of stacked thrust sheets, composed of uppermost Neoproterozoic and Phanerozoic sedimentary strata approximately 7 to 12 kilometers thick, in the external part of the southwest-migrating Zagros orogenic wedge (Alavi, 1991, 1994).

The latest systematic account of the stratigraphy of the Zagros fold-thrust belt is that of James and Wynd (1965), which includes only Mesozoic and Cenozoic units. More recent investigations have added considerable amounts of information which require a more comprehensive analysis and major revision of the stratigraphy of the region. Specifically, it is now well-established that a significant part of the stratigraphy of the Zagros fold-thrust belt developed in an epicontinental, synorogenic proforeland basin, whose evolution has been intimately related to the tectonic and structural events of the associated Zagros orogen.

Foreland basins, as synthesized by DeCelles and Giles (1996), have attracted the attention of many earth scientists. Being the sites of favorable conditions of hydrocarbon generation, migration, and accumulation, they have been the subjects of a considerable number of stratigraphic, sedimentological, structural, and geodynamic studies. The Zagros proforeland basin (being a specific type within the general category of the foreland systems; for terminology see: Willett and others, 1993; Johnson and Beaumont, 1995), as an integral part of the Zagros fold-thrust belt, with all its economic significance, however, has remained problematic. In Iran, geological investigations of the Zagros fold-thrust belt have extended over nearly a century since the earliest petroleum discovery in the region, and many petroleum geologists have contributed significantly to a better understanding of the geology of this petroliferous tectonosedimentary zone (Lees, 1950; Falcon, 1958, 1974; Dunnington, 1958, 1967; James and Wynd, 1965; Mina and others, 1967; Kamen-Kaye, 1970; Szabo and Kheradpir, 1978; Setudehnia, 1978; Murris, 1980; Koop and Stoneley, 1982; Beydoun and others, 1992; and Alsharhan and Nairn, 1997, among others). In these contributions, the belt has frequently been referred to as a "foreland" or "foredeep" basin, but no detailed accounts have been presented of the stratigraphic architecture and various depozones, nor have specific correlations been suggested between sedimentological evolution and related tectonic events that shaped the interior part of the orogen. In recent years, as a result of extensive geological mapping in various segments of the internal and external parts of the orogen (for example, Alavi, 1994, 1997; Alavi and Mahdavi, 1994; Ehsanbakhsh, 1996; Nazari and Shahidi, 1998; Talebian, 1999; Karimi-Bavandpour, 1999; Mohajjel and Fergusson, 2000), a better understanding of the evolution of this mountain belt and its proforeland basin has emerged. Recent detailed investigations concerning sedimentological aspects of the Iranian segment of the basin in the context of a better-constrained tectonic framework, and the areal distributions and interrelationships of rock units in light of new developments in sequence stratigraphy and deformation/sedimentation relationships, as well as geodynamic concepts, have resulted in a more comprehensive stratigraphy. Such work forms the basis for a synthesis of the uppermost Neoproterozoic through Phanerozoic successions, and provides a framework upon which a scheme for Zagros proforeland evolution can be established.

TECTONIC SETTING

The Zagros orogen (fig. 1) is interpreted as the product of three major sequential geotectonic events: (1) subduction of the Neo-Tethyan oceanic plate beneath the Iranian lithospheric plates during Early to Late Cretaceous time, (2) emplacement ("obduction") of a number of Neo-Tethyan oceanic slivers (ophiolites) over the Afro-Arabian passive continental margin in Late Cretaceous (Turonian to Campanian) time, and (3) collision of the Afro-Arabian continental lithosphere with the Iranian plates in Late Cretaceous and later times (Alavi, 1994). The orogen is bounded to the northwest by the East Anatolian left-lateral strike-slip fault (EAF) and to the southeast by the Oman Line (OL) (Falcon, 1969), which is here considered to be a transform fault inherited from the opening of Neo-Tethys. The orogen consists of three parallel belts: (1) the Urumieh-Dokhtar magmatic assemblage (UDMA), which forms a subduction-related, distinctively linear and voluminous magmatic arc composed of tholeiitic, calc-alkaline, and K-rich alkaline intusive and extrusive rocks (with associated pyroclastic and volcaniclastic successions) along the active margin of the Iranian plates; (2) the Zagros imbricate zone (ZIZ) (the "Sanandaj-Sirjan Zone", as redefined by Alavi, 1994, after Stocklin, 1968a, 1977), which is a zone of thrust faults that have transported numerous slices of metamorphosed and non-metamorphosed Phanerozoic stratigraphic units of the Afro-Arabian passive continental margin, as well as its "obducted" ophiolites, from the collisional suture zone on the northeast toward interior parts of the Arabian craton to the southwest; and (3) the Zagros fold-thrust belt (ZFTB), which forms the less strained external part of the orogen, and consists of a pile of folded and faulted rocks composed of 4 to 7 kilometers of mainly Paleozoic and Mesozoic successions overlain by 3 to 5 kilometers of Cenozoic siliciclastic and carbonate rocks resting on highly metamorphosed Proterozoic Pan-African basement that was affected by the late Neoproterozoic–Cambrian Najd strike-slip faults (for example, Brown and Jackson, 1960; Moore, 1979; Agar, 1987; Husseini, 1988). The southwestern boundary of the Zagros fold-thrust belt defines the present-day Zagros deformational front (ZDF), to the southwest of which deformation has not yet propagated.

STRATIGRAPHY

More than a hundred stratigraphic columns have been studied from both subcrop (well) and outcrop (measured) sections in various parts of the Zagros belt. Based on this database and available published and unpublished stratigraphic, sedimentological, and petrographic information, as well as field and laboratory observations by the author, a description for each stratigraphic unit (not necessarily all at formational rank) has been prepared (see appendix).

The latest Neoproterozoic–Phanerozoic stratigraphy of the Zagros fold-thrust belt is represented by four major groups of rocks that are defined based on their tectonosedimentary features. Each group consists of a number of unconformity-bounded megasequences, each of which represents a discrete sedimentary cycle and consists of a number of lithostratigraphic units (fig. 2).

Neoproterozoic to Devonian(?) Pull-apart and Epicontinental Platform Basins

The oldest group comprises the uppermost Neoproterozoic to Devonian(?) marine and nonmarine deposits which consist of a thick unit of evaporites and associated volcanic and sedimentary layers at the base, and overlying siliciclastic (partly fluvial) and carbonate rocks that are interrupted by several regionally significant unconformities at various stratigraphic levels (fig. 2). Uppermost Neoproterozoic and Lower Cambrian part of this group (megasequence I) is thought to have accumulated in an extensional pull-apart setting related to the late Precambrian–early Cambrian Najd strike-slip fault system that affected the northeastern part of the Gondwanan landmass(es) (Husseini, 1989; Talbot and Alavi, 1996). Middle and upper Cambrian strata (Mila Formation), separated from the underlying megasequence by a sharp disconformity (see appendix), form a transgressive/regressive carbonate-dominated megasequence (II), including basal white orthoquartzites and quartzarenites, which deposited on a continental platform. The tectonosedimentary setting of the post-Cambrian but pre-Permian strata is uncertain, owing to scarcity of outcrops and major regional unconformities (fig. 2). The presence of volcanogenic layers in the younger stratigraphic units (for example, Zard Kuh), suggests a relationship to the development of the Paleo-Tethyan ocean, whose opening in early Paleozoic time is well documented in the Alborz belt of northern Iran (Alavi, 1996).

Two pre-Permian units have had a significant impact on the structural evolution and stratigraphy of the region. First, the uppermost Neoproterozoic–Cambrian evaporites (the Hormuz "series"), wherever present, acted as an important detachment horizon during structural evolution of the fold-thrust belt, and have complicated the structural pattern of the region by forming numerous complex salt diapirs (for example, Kent, 1958; Falcon, 1969; Talbot and Jarvis, 1984; Alavi, 1994; Talbot and Alavi, 1996). Second, Silurian graptolitic shales (Gahkum), although removed from many areas during several Paleozoic erosional episodes, have been a source for hydrocarbons in Permian–Triassic reservoirs (Bordenave and Burwood, 1990).

Permian to Triassic Epi-Pangean Platform

Uppermost Neoproterozoic to Devonian(?) group is overlain unconformably by the basal conglomerates and sandstones of the overlying epi-Pangean platform succession of Permian to Triassic age (Szabo and Kheradpir, 1978; Sharief, 1982; Ghavidel Syooki, ms, 1988). The Permian–Triassic strata were deposited in a very shallow and

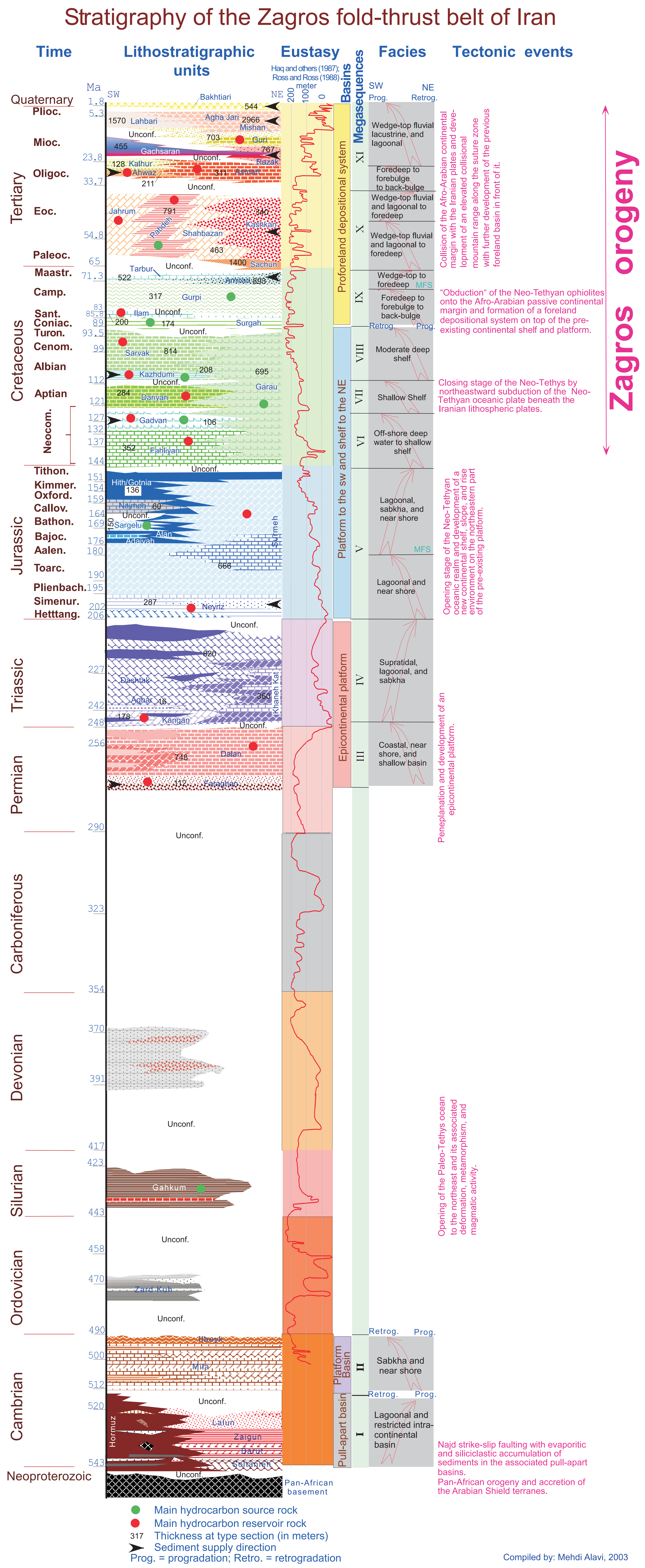

Fig. 2. Stratigraphy of the Zagros fold-thrust belt of Iran. Geologic time scale after Palmer (1983) and Landing and others (1998). See appendix for descriptions of rock units.

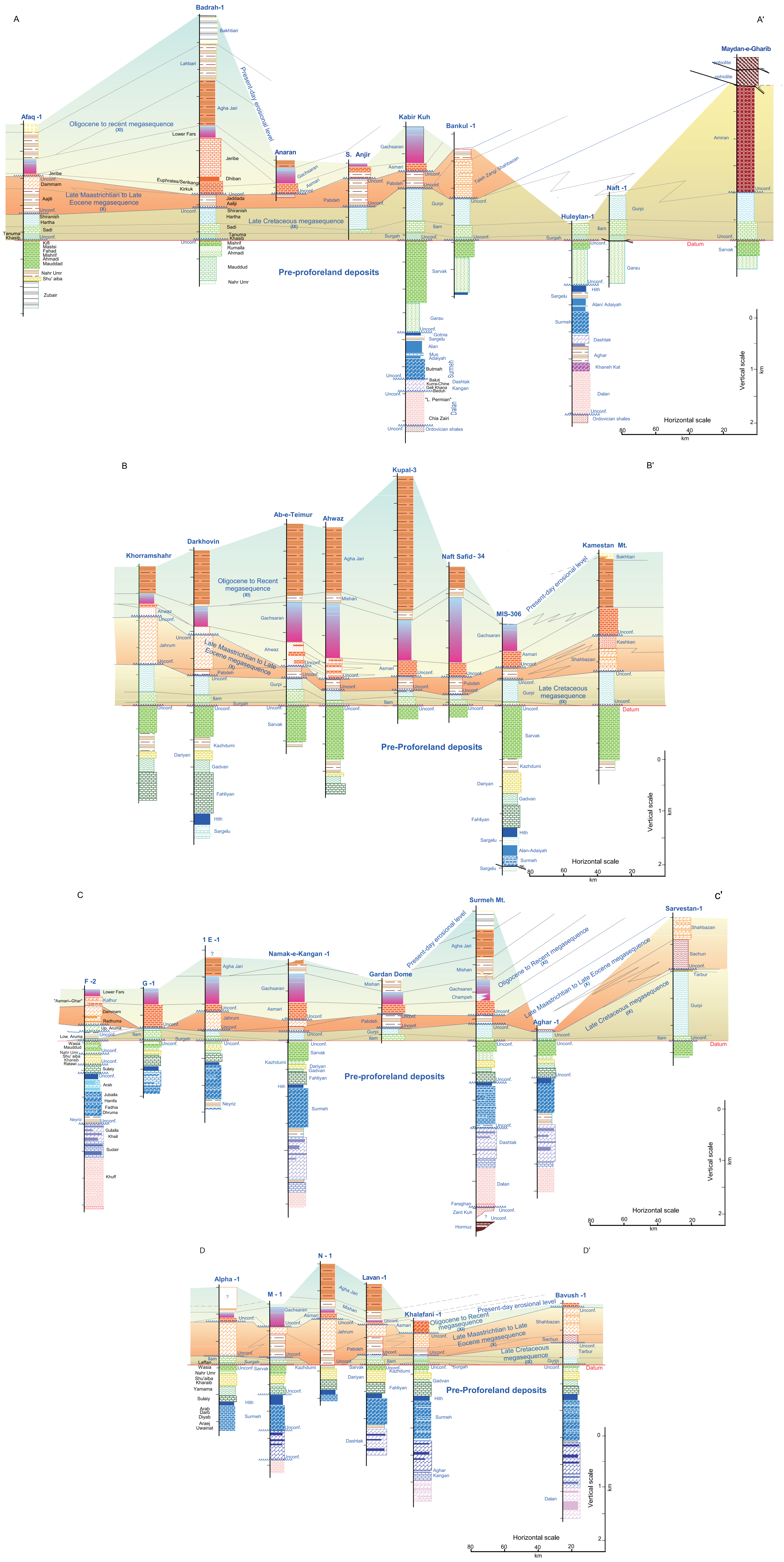

Fig. 3. Four stratigraphic correlation profiles across the Zagros fold-thrust belt of Iran. See figure 1 for locations of the stratigraphic profiles. Three megasequences (IX, X, and XI of fig. 2) of the proforeland basin are distinguished. The stratigraphic columns are restored to their pre-Zagros-deformation positions. The latest Turonian regional unconformity is chosen as the datum. Non-Iranian stratigraphic nomenclatures are shown in black.

warm paleoequatorial sea, and constitute two megasequences (III and IV) separated by a disconformity at the Permian/Triassic boundary (fig. 2). These two megasequences together form one of the most prolific gas-prone plays in the world.

The Permian megasequence (III) was deposited diachronously by transgression from the northeast over a platform flanking Pangea, and consists of basal red polymict pebble conglomerate, and arkosic and quartzose sandstones. Subsequent retrogradation formed overlying Upper Permian interlayered dolomites and evaporites (southwest), as well as high-energy bioclastic limestones (northeast). The megasequence extends laterally toward the east and northeast into time-equivalent, now partly metamorphosed, fusulinid-bearing platform clastic and carbonate rocks mapped within the Zagros imbricate zone (Alavi, 1997) and central Iran (Mahdavi, 1995).

The Triassic megasequence (IV) consists of a succession of northeastward prograding, interbedded evaporites and dolomites with interlayers of shallow-marine but low-energy limestones to the northeast. An unconformity, correlative with the well-known late Triassic unconformity of the Zagros imbricate zone, separates this megasequence from overlying Jurassic to Cretaceous continental-shelf deposits. Development of the unconformity was associated with extensional tectonic activity, plutonism, volcanism, and metamorphism in the Zagros imbricate zone (Alavi, 1994). In the Zagros fold-thrust belt, it appears as a distinctive sharp disconformity under which Triassic evaporites and dolomites are locally (in Lorestan and Khuzestan provinces) eroded away or reduced to less than 250 meters in thickness. The unconformity is attributed to extensional faulting, which was in progress farther to the northeast along the continental margin during the opening of the Neo-Tethyan oceanic realm.

Jurassic to Upper Cretaceous Neo-Tethyan Continental Shelf

Overlying the Permian–Triassic platform successions, lowermost Jurassic to upper Turonian strata (James and Wynd, 1965; Kheradpir, 1975; Khalili, 1976; Shakib, 1990) form a number of megasequences (V through VIII of fig. 2) that accumulated on a shallow continental-shelf, facing north and northeast toward Neo-Tethys in a paleoequatorial setting. Megasequences V to VIII contain many petroleum source and reservoir rocks, as well as seals (for example, Ala and others, 1980; Stoneley, 1990; Bordenave and Burwood, 1990; Beydoun and others, 1992). The megasequences are separated from one other by distinct disconformities, but mark only short hiatuses. The lowermost unit of this group, the Neyriz Formation of earliest Jurassic age (Wynd, 1965), received argillaceous and sandy detritus from a sediment source to the northeast, most probably formed by fault-bounded ridges associated with extensional break-up of the continent at the time of Neo-Tethys opening. The overlying units of megasequences V to VIII all display gradual facies changes from coastal and sabkha-type clastic strata, evaporites, and dolomites on the southwest to shallow-water, high-energy-environment limestones, and finally to deep-marine, pelagic and hemipelagic lime mudstones and marls on the northeast. The facies changes have been recognized at various stratigraphic levels, and are thought to be at least partly a result of reactivation of pre-existing, predominantly north–south trending structural elements inherited from underlying Neoproterozoic Pan-African belts. This concept of reactivation of older structures is supported by the observation that thicknesses of some stratigraphic units change abruptly within short distances. For example, the uppermost Jurassic to lower Cretaceous Fahliyan, Gadvan, and Dariyan inner and outer shelf carbonates and argillites (Shakib, 1994), which are collectively about 750 meters thick in the central part of the belt (Khuzestan province), but thin to the southeast (Fars Province) to only 250 to 300 meters in thickness (compare stratigraphic columns of profile B–B′ with those of the C–C′ in fig. 3). This change occurs across a north–south trending lineament known as the Qatar–Kazerun line, whose structural characteristics are discussed by Falcon (1969), Pattinson (1970), Pattinson and Takin (1971), and Baker and others (1993).

Latest Turonian to Recent Proforeland Basin

The shelf successions are overlain unconformably by upper Cretaceous to Recent marine, paralic, and continental deposits, derived mainly from the northeast and including siliciclastic strata, shallow- and deep-marine carbonates, and restricted-depozone evaporites. Facies and thickness variations define an elongate, asymmetrical, dynamically fluctuating, forward and backward migrating, proforeland basin that has evolved along a northwest–southeast trend in front of the active Zagros orogenic wedge. The proforeland deposits (megasequences IX, X, and XI of fig. 2) of the Zagros fold-thrust belt form only part of the foreland system, for erosion removed the orogenic flank of the proforeland basin during folding, faulting, and uplift of the Zagros imbricate zone. Only thin erosional remnants of the proforeland strata have been mapped locally in the Zagros imbricate zone (for example, Alavi and Mahdavi, 1994; Alavi, 1997).

Tapering toward the southwest, proforeland strata onlap partly eroded underlying strata and pinch out laterally against subaerial unconformities. The cumulative thickness of siliciclastic proforeland strata, based on measurements at the type sections of various stratigraphic units, is estimated as 6480 meters, and that of marine carbonates deposited in the deepest parts of the basin (foredeep depozone) as 1940 meters. No economically significant hydrocarbons are found in the northeasterly-derived siliciclastic wedges along the northeast flank of the basin, but units that display facies characteristics representative of both the low-energy deeper parts and the high-energy shallower parts of the basin interior form outstanding source and reservoir rocks. Seals are either evaporites or deep-marine calcareous shales, marls, and argillaceous lime-mudstones.

Proforeland Megasequences

Three proforeland megasequences (IX, X, and XI of fig. 2) extend parallel to the general trend of the mountain belt, each displaying internal vertical and lateral facies variations. The following tectonosedimentary analysis is based on lithofacies characteristics and the stratal architecture of time-correlative strata representing various depozones within the basin. Four representative stratigraphic profiles across the belt show correlations of the proforeland strata (fig. 3). In these profiles, utilizing retrodeformable balanced structural cross-sections, the locations of the stratigraphic columns are restored to their original, pre-Zagros-deformation positions. A generalized correlation of various prograding and retrograding facies, deposited in different depozones of the foreland system, is presented in figure 4. Lithofacies considerations (see below) reveal that the basin has been predominantly an underfilled one (in the sense of Flemings and Jordan, 1989). Structural interpretations are made, therefore, assuming that loading due to sediment accumulation has been subordinate relative to thrust loading along the flank of the orogen. Moreover, the changing position of the forebulge depozone through time, with respect to foredeep and back-bulge depozones, suggests that tectonic factors have played the major role in providing accommodation space for sediment accumulation and that sea-level fluctuations (see eustatic curve in fig. 2) have had only minor effects in shaping the stratigraphic architecture of the basin.

Late Cretaceous megasequence (~90 to 68 Ma).—The oldest proforeland megasequence (IX of fig. 2), of latest Turonian to middle Maastrichtian age, includes the Surgah, Ilam, Gurpi, Amiran, and Tarbur formations (see appendix), which form a progradational–retrogradational package of strata bounded by two major unconformities (figs. 3 and 4). The basal unconformity is a hematite-stained, erosional surface, locally associated with conglomerates composed of reworked carbonate clasts (Stoneley, 1990), and represents a hiatus of approximately 4 to 15 my. To the southeast (Fars province), the unconformity is the contact between basal Gurpi marls of Santonian (~84 Ma) age which overlie lower Cenomanian (~96 Ma) Sarvak limestones of Albian to Turonian age. Farther northwest, in the central part of the Persian Gulf, where the middle and upper parts of the Sarvak Formation are missing, Santonian shales of the Surgah (or Laffan) Formation overlie the lower (most probably Albian) part of the Sarvak along a ferruginous weathering surface. In Khuzestan, Ilam limestones of Santonian age overlie lower Turonian Sarvak strata; again the contact is a sharp weathering surface. Farthest northwest (Lorestan province), ferruginous Sarvak limestone of Turonian age, with a yellowish, limonite-rich, weathered layer 1 meter thick at the top, underlies Santonian shale of the Surgah Formation.

The top of the Late Cretaceous megasequence is defined by a subaerial unconformity that separates basal strata of the overlying megasequence (X of fig. 2) from middle Maastrichtian strata. In Lorestan and Khuzestan provinces, the Paleocene to Eocene Pabdeh Formation, with a thin (1–3 m), purple, sandy to silty and locally conglomeratic, shale layer at the base, overlies the top of weathered, glauconitic, phosphorite-rich Gurpi Formation (fig. 3), indicating a significant erosional unconformity. Paleontological data (Wynd, 1965) suggest that the unconformity represents a hiatus of about 10 my. In the northeastern parts of Lorestan and Khuzestan provinces, the unconformity is a sharp contact between either Paleocene Shahbazan (including Taleh Zang; see appendix) strata of bioclastic limestones and underlying Maastrichtian Amiran siliciclastic rocks, or between fluvial conglomerates of the Paleocene Kashkan Formation and underlying carbonates of the Tarbur Formation.

To the southeast, in Fars province, the unconformity has the same characteristics (see profiles C–C′ and D–D′ in fig. 3), except that local erosion (for example, well N - 1 in profile D–D′, fig. 3) prior to deposition of the Pabdeh Formation removed not only the entire Late Cretaceous megasequence but also underlying Sarvak carbonates, so that basal strata of the Pabdeh rest directly on weathered and glauconitic calcareous shale of the Albian Kazhdumi Formation. Southwestward, where the Pabdeh Formation is replaced laterally and gradationally by Jahrum dolomites (see appendix), the unconformity again displays characteristics of a subaerial weathering surface, which is associated with a thin layer of hematite-stained, sandy and glauconitic shale or argillaceous lime mudstone. To the northeast, in the interior parts of the belt, the unconformity separates fine-grained and evaporitic shales and carbonates (paralic with local fluviatile conglomerates) of the latest Maastrichtian to Paleocene Sachun Formation, or coarse-grained fluvial Kashkan conglomerates, from underlying weathered (hematite-stained) and partly reefal Tarbur carbonates. Locally, the Sachun Formation is missing and, instead, the Shahbazan Formation (previously referred to as "Jahrum" in this part of the Zagros fold-thrust belt, see appendix) is in unconformable contact with underlying Tarbur carbonates.

The internal stratigraphic architecture of the Late Cretaceous megasequence (IX) is defined by the spatial arrangement of various lithofacies of different stratigraphic units. To the northeast of the Zagros fold-thrust belt, in thrust slices of the Zagros imbricate zone, ophiolites are thrust onto the Sarvak Formation (or its time-equivalent carbonates), and have metamorphosed them locally. In the interior parts of the Zagros fold-thrust belt, fluvial conglomerates and sandstones of the Amiran Formation, which were derived from the ophiolite complexes (James and Wynd, 1965; Alavi, 1994), as a prograding siliciclastic wedge grade laterally in a southwestward direction to the alternating greenish-gray paralic siltstones, glauconitic sandstones, and dark gray shales ("flysch") which interfinger with the Gurpi Formation. Farther to the southwest, the Amiran Formation pinches out, and *Globotruncana*-bearing argillaceous lime mudstones of the Gurpi Formation, with deep-marine lithic and faunal characteristics, overlie Sarvak limestones. In the external part of the Zagros fold-thrust belt, near the Zagros deformational front (fig. 1), the Gurpi Formation unconformably overlies shallow-marine limestones of the Ilam Formation, which includes several hematite-stained subaerial intraformational disconformities and disconformably overlies argillites, argillaceous lime mudstones, and wackestones of the Surgah Formation. Still farther to the southwest, the Surgah grades laterally into time-equivalent Laffan Formation (lowest part of the Aruma Group) in the United Arab Emirates, Qatar, and Bahrain, and into the Khasib and Tanuma Formations in Kuwait and southern Iraq (fig. 3). These units onlap underlying weathered older strata and pinch out against a regional subaerial unconformity that is well documented in the stratigraphy of the southwestern Persian Gulf states, as well as in Saudi Arabia (Steineke and others, 1958; Powers and others, 1966; Peterson and Wilson, 1985; Alsharhan, 1989; Jones and Racey, 1994).

At a higher stratigraphic level (middle Maastrichtian), the Gurpi Formation is conformably overlain by Tarbur carbonates. The Tarbur Formation transgressively expands towards the northeast well into the Zagros imbricate zone, and shows distinctive lateral facies variations. In the external part of the belt, the Tarbur Formation consists of thin-bedded pelagic and hemipelagic marls and argillaceous lime mudstones with planktonic foraminiferal faunal assemblages (Wynd, 1965); in this part of the region, having a gradational contact with the underlying Gurpi Formation, the two formations are practically indistinguishable from each other. To the northeast, in the internal parts of the Zagros fold-thrust belt, the Tarbur Formation unconformably onlaps either the ophiolite complexes (with a basal 2-m-thick polymict pebble-conglomerate layer) or the Amiran Formation, and is composed of shallow-water (littoral-zone) limestones with high-energy characteristics including biohermal reef build-ups. In this internal part of the belt, the Tarbur carbonates interfinger with gypsum and dolomite layers of the lower part of the Sachun Formation. In the external part of the belt, however, late Maastrichtian to earliest Paleocene erosion removed the upper part of the Tarbur, and the relationship between this unit and the Ilam and Surgah formations to the southwest is uncertain; presumably, these two units, following the Tarbur Formation and onlapping it, also migrated towards the northeast (fig. 5).

The development of the late Cretaceous megasequence (IX) is interpreted to reflect emplacement of Neo-Tethyan ophiolites onto the Afro-Arabian passive continental margin, and the subsequent initial collisional stage of this margin with the Iranian plates, associated with intense, southwestward-directed thrust stacking (fig. 5A and B). The emplacement of the ophiolites and associated thrust sheets presumably exerted a considerable load on the Afro-Arabian continental margin, which resulted in development of a foredeep and associated forebulge and back-bulge depozones in front of them. The process of emplacement of thrust sheets began in latest Turonian and lasted until the Maastrichtian, a time period of about 15 my. The erosional products of the ophiolite components, revealing preserved growth strata (in the sense of Suppe and others, 1992) associated with development of fault-propagation folds, formed the wedge-top deposits of the Amiran Formation with its proximal facies conglomerates and sandstones, and alternating sandstones and shales ("flysch") of more distal facies. During this period, the hemipelagic sediments of the Gurpi Formation filled the foredeep, while shallow-water carbonates of the Ilam Formation accumulated on the forebulge and the calcareous argillites and argillaceous lime mudstones of the Surgah (or Laffan) were deposited in the back-bulge depozone. The presence of cannibalized and reincorporated pebbles, cobbles, and boulders of Amiran conglomerates (see appendix), as well as the existence of growth strata in this formation, suggest that the processes of uplift and thrust faulting were still in progress during deposition of the

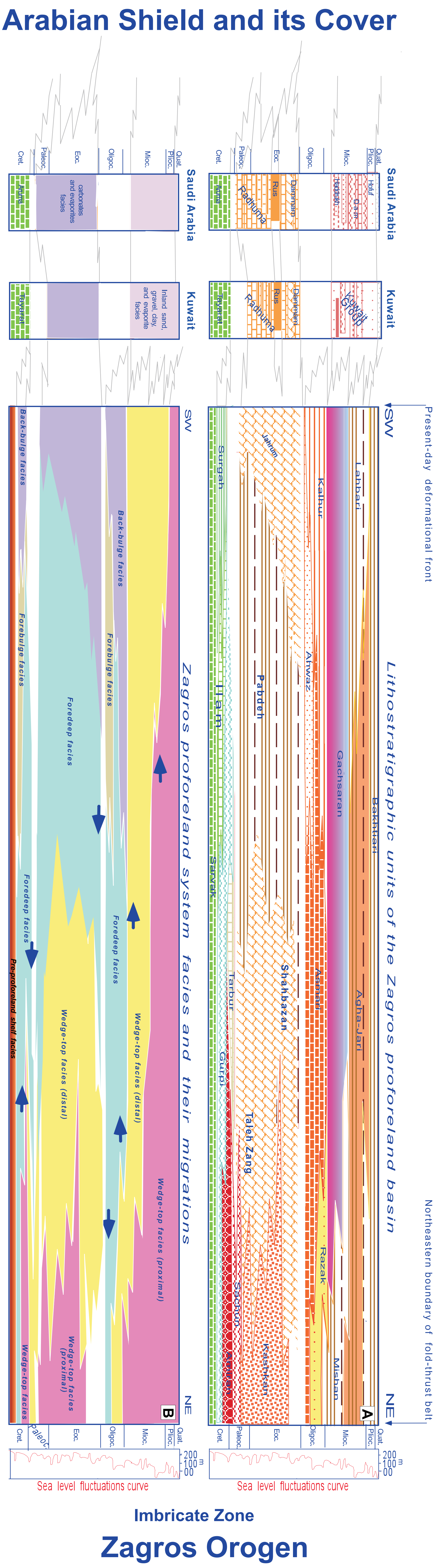

Fig. 4. (A) Lithofacies variations of proforeland stratigraphic units across the Zagros fold-thrust belt of Iran. (B) Interpreted migration (arrows) of various depozones within the basin. Stratigraphic columns for Saudi Arabia and Kuwait are based on Steineke and others (1958), Owen and Nasr (1958), Powers and others (1966), Peterson and Wilson (1986), Alsharhan (1989), Jones and Racey (1994), and Alsharhan and Nairn (1997). Sea-level fluctuation curve is after Haq and others (1987).

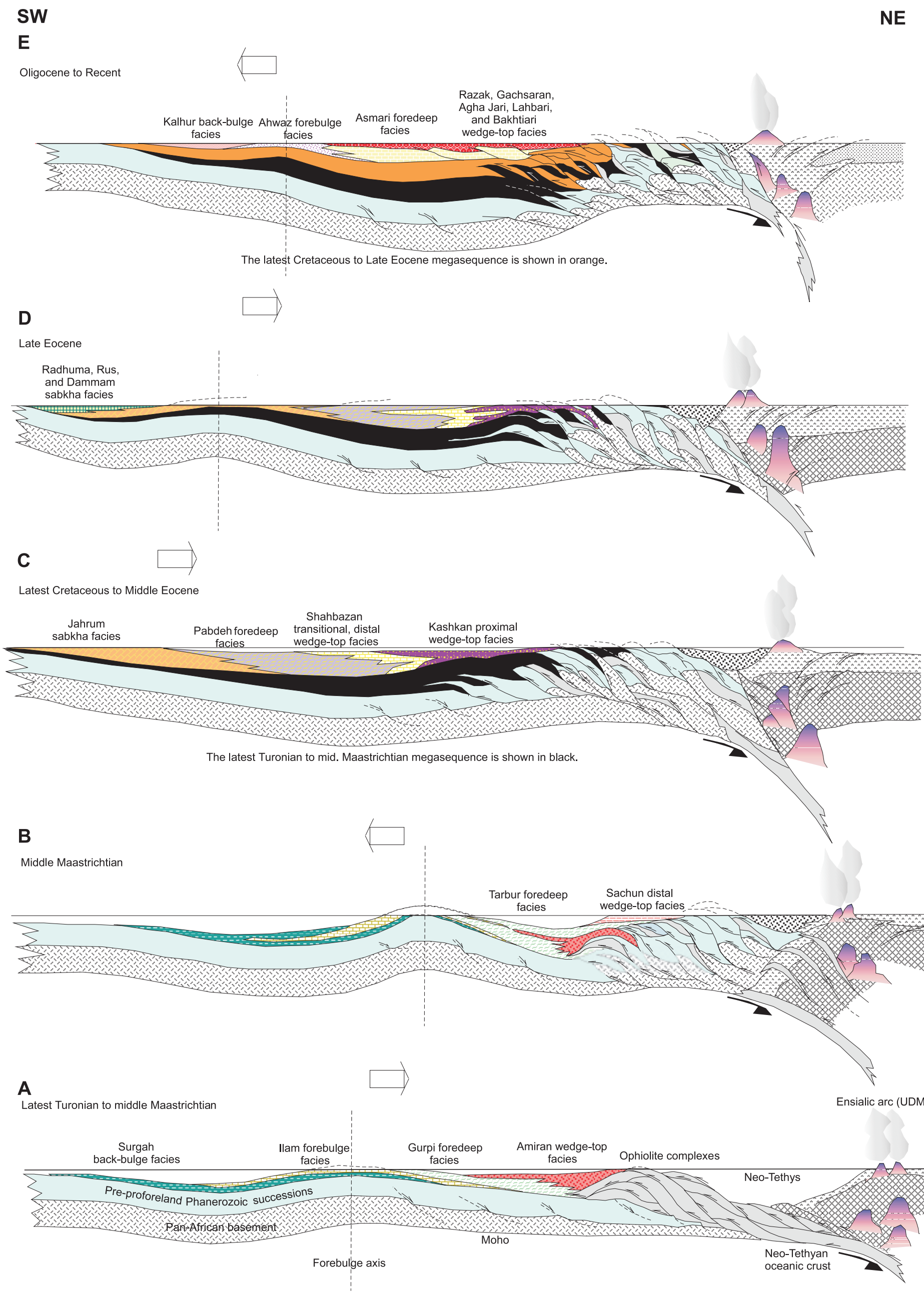

Fig. 5. Sequential schematic diagrams showing evolution of the Zagros proforeland basin in response to Zagros tectonic events. Dashed line is a reference line showing axis of the forebulge. Large arrows show the direction of forebulge migration. For simplicity, the latest Turonian to middle Maastrichtian megasequence (IX), whose evolution is shown in A and B, is represented by solid black pattern in C, D, and E, and the latest Cretaceous to Late Eocene megasequence (X) shown in C and D is represented by orange color in E.

Amiran Formation. The southwestward onlapping relationships between the Gurpi and Ilam formations, as well as between the Ilam and Surgah, are thought to reflect the southwestward migration of the basin depozones (fig. 4).

During middle Maastrichtian time, deep-facies foredeep carbonates of the Tarbur Formation expanded towards the hinterland (northeast), and time-equivalent shallow-marine reefal carbonates transgressively covered subaerially exposed ophiolites and Amiran siliciclastic sediments (fig. 5B). Northeastward retrogradational migration of the foredeep and associated depozones of the proforeland basin is interpreted as a response to intensified thrust stacking and consequent enhanced loading of the lithosphere along the edge of the Afro-Arabian continent as it began to collide with the Iranian plates. Thus, the initiation of the collisional episode of the Zagros orogeny is considered to be a middle Maastrichtian event (~68 Ma).

Latest Maastrichtian to Late Eocene megasequence (~66 to 35 Ma).—The second proforeland megasequence (X of fig. 2), unconformably overlying the Late Cretaceous megasequence (IX), includes the Sachun, Kashkan, Shahbazan, Pabdeh, and Jahrum stratigraphic units (figs. 3 and 4). From northeast to southwest, uppermost Cretaceous to middle Eocene strata are progradational, whereas overlying middle to upper Eocene strata reveal retrogradational arrangement.

The lowest unit (Sachun Formation) is restricted to the northeastern internal part of the Zagros fold-thrust belt, and consists of evaporites and thin dolomites interbedded with red shales and sandstones becoming sandier and more argillaceous to the northeast and interfingering in that direction with the Kashkan Formation. The Kashkan, which is composed of conglomerates and coarse-grained sandstones on the northeast and of shales interbedded with fine-grained sandstones on the southwest, progradationally overlies the Sachun Formation and interfingers with Shahbazan (or Taleh Zang, see appendix) dolomitic and detrital limestones. The Shahbazan Formation forms a transitional facies between fluviatile siliciclastic strata of the Kashkan Formation and deep-water facies lime mudstones, calcareous shales, and marls of the Pabdeh Formation. To the southwest, the Pabdeh grades laterally into sabkha-type dolomites and evaporites of the Jahrum Formation. The Jahrum, in turn, extends southwestward toward similar time-equivalent facies of the Radhumma-Rus-Dammam formations of Kuwait and Saudi Arabia, which onlap and pinch out against a subaerial unconformity (Owen and Nasr, 1958; Powers and others, 1966). This progradational stratigraphic arrangement is inverted in the middle to upper Eocene part of the megasequence in which retrogradational Pabdeh Formation transgressively onlaps Shahbazan carbonates in a northeastward direction, and Shabazan carbonates in turn overlie Kashkan conglomerates (fig. 4). Near the present-day Zagros deformational front (ZDF), the upper part of the megasequence, composed of deep-marine argillites and carbonates of the Pabdeh is overlain by Jahrum dolomites, again indicating northeastward migration of basin depozones.

The top of megasequence X is truncated by a regional subaerial unconformity (figs. 3 and 4). The unconformity is defined as the Asmari/Jahrum contact in the external part of the belt; it is distinguished by a layer of irregularly-bedded, hematite-stained dolomites and pebble conglomerates. Uppermost Eocene strata of the Jahrum were erosionally removed before Asmari deposition, and the lower part (lower Oligocene) of the Asmari succession is not present. To the southwest, near the present-day Zagros deformational front, where Jahrum dolomites are overlain by Ahwaz sandstones (see fig. 3, profile B–B′), subsurface paleontological data from Kharg and Darkhovin boreholes (Adams, 1969) suggest an early Miocene age for the lowest beds of the Ahwaz and a middle Eocene age for the uppermost strata of the Jahrum, indicating a hiatus of ~ 20 my. Farther southwest, outside of the Zagros fold-thrust belt (for example, in Kuwait and southern Iraq), the same unconformity is recognized between lower Miocene Ghar sandstones (an equivalent of the upper part of the Ahwaz) and the underlying Dammam (Jahrum-equivalent) dolomites (Owen and Nasr, 1958; Al Naqib, 1967).

Towards the northeast, along the central part of the Zagros fold-thrust belt, where the Jahrum Formation is missing, coarse-grained, thick-bedded, dolomitic Asmari limestones, deposited in high-energy environments, overlie fine-grained, very thinly- and uniformly-bedded and locally limonitic, calcareous argillites and argillaceous limestones of the middle part of the Pabdeh Formation. The contact between the Asmari and Pabdeh formations is an erosional unconformity, where upper parts of the Pabdeh were removed by erosion. Farther northeast, in the interior part of the belt, upper strata of the Eocene Shahbazan carbonates are also partly missing at the unconformity, and lower Shahbazan strata, capped by a layer of low-weathering, rubbly limestone formed by solution brecciation, underlie either middle Oligocene Asmari limestones or lower Miocene (Burdigalian) Razak evaporitic and siliciclastic strata.

Facies variations within megasequence X reveal aspects of the evolution of the proforeland basin in response to prevailing tectonic events from latest Maastrichtian to late Eocene time (fig. 5C and D). Progressive collisional deformation (mainly as thrust stacking of upper crustal slivers), which had started in middle Maastrichtian time, resulted in formation of an elevated mountain range that acted as a major source of polymict siliciclastic sediment supplied to the basin during latest Cretaceous, Paleocene, and early–middle Eocene times. The upper part of the Sachun Formation and the lower part of the Kashkan Formation are interpreted respectively as distal and proximal facies of a prograding clastic wedge-top depozone. The Pabdeh deep-marine facies represents deposits of the foredeep, on the northeastern shallow side of which Shahbazan sandy and argillaceous carbonates were deposited as a transitional facies between the Pabdeh foredeep facies and the distal Sachun facies of the wedge-top depozone.

On the southwestern side of the basin, no forebulge and back-bulge depozones can be distinguished. The lower part of the Pabdeh grades laterally into carbonates and evaporites of the Jahrum Formation (figs. 3 and 4). The lack of recognizable forebulge or back-bulge facies may be due to the low resolution of available sedimentological and stratigraphic data, but it can be attributed alternatively to an overall reduction in contractional tectonic activity of the orogen during Paleocene to middle Eocene time (fig. 5C). In this latter case, one can hypothesize that a decrease in the rate of thrust stacking and a consequent decrease in addition of excess load applied to the continental margin, as well as removal of pre-existing uplifted rocks by erosion and (or) tectonic denudation, resulted in migration of the basin away from the orogenic wedge and gradual reduction in the amplitude of the forebulge. This style of tectonic behavior perhaps explains the gradational change from the Pabdeh foredeep facies to the sabkha-type carbonates and evaporites of the Jahrum Formation.

In the upper part of megasequence X (middle to upper Eocene), stratigraphic relationships between various facies are opposite to those of the lower part. In the upper part, the Pabdeh Formation onlaps the Shahbazan carbonates in a northeastward direction, and Shahbazan in turn retrogradationally overlies Kashkan conglomerates (fig. 4). On the southwestern side of the basin, also, the Jahrum onlaps the Pabdeh Formation in a northeastward direction. These relationships, which are similar to those of the middle Maastrichtian rocks of underlying megasequence IX are interpreted (fig. 5D) to be a result of the response of the basin floor to a new phase of loading of the continental margin by intensified thrust faulting in the hinterland region, which itself may suggest an increase in convergence rate at the suture zone. During this postulated episode of intensification of the tectonic activity, the basin is inferred to have migrated toward the hinterland (northeast), while uplift of a freshly elevated forebulge resulted in erosional removal of strata during development of the late Eocene unconformity.

Oligocene to recent megasequence (~33 Ma to present).—The third proforeland megasequence (XI of fig. 2) includes the Razak, Asmari, Ahwaz, Kalhur, Gachsaran, Mishan, Agha Jari, Lahbari, and Bakhtiari stratigraphic units, which collectively form an upward-coarsening, southwest-prograding succession. The lowest units, which rest on the late Eocene unconformity (figs. 3 and 4), include from northeast to southwest the Razak, Asmari, Ahwaz, and Kalhur. The Razak Formation consists of interfingering thin carbonates and calcareous argillites toward the southwest and of interbedded shales, siltstones, sandstones, and conglomerates toward the northeast. Razak facies relations suggest that the coarser siliciclastic strata may have existed farther to the northeast in the Zagros imbricate zone, but were removed erosionally and (or) denudated tectonically after deposition. To the southwest, the Razak Formation grades laterally to Asmari carbonates, which progradationally overstep Ahwaz quartz-bearing sandstones (fig. 3). The Ahwaz sandstones, whose distribution along the strike of the basin is restricted (see appendix), are shoreface deposits forming a number of elongate northwest–southeast trending and northeastward-thinning parasequences displaying rapid lateral facies variations. Their distributions and lithic characteristics are indicative of repeated subaerial exposures, most probably induced by tectonic uplift. Farther southwest, the Ahwaz stratigraphic unit grades into the Kalhur evaporites, argillaceous lime mudstones, and dolomites. Towards the southwest (in Kuwait and Iraq), Kalhur onlaps underlying strata and pinches out against an Oligocene subaerial regional unconformity (fig. 4) (Al Naqib, 1967; Adams, 1969).

In the lower part of megasequence XI, the Razak Formation is interpreted as the distal facies of a clastic wedge whose proximal facies presumably extended to the northeast into the Zagros imbricate zone but has been eroded away. The wedge progradationally overlapped deeper-facies Asmari carbonates, which can be interpreted as a foredeep facies (fig. 5E). The Ahwaz sandstones are inferred to have been deposited in a high-energy forebulge depozone that was overstepped by foredeep Asmari carbonates. Evaporites and calcareous argillites of the Kalhur may represent deposits of a low-energy, coastal to nearshore environment in the back-bulge depozone whose deeper part is represented by lime mudstones of the same unit.

The overlying stratigraphic units in the upper part of megasequence XI, are truncated to the southwest beneath recent coastal sand, gravel, clay, and evaporites of the Arabian platform (figs. 3 and 4), but show a continuation of progradation of siliciclastic strata (coarse-grained to the northeast and fine-grained to the southwest) in a southwestward direction through time. The stratigraphic units in the upper part of the megasequence, display syndeformational sedimentary features such as growth strata (see appendix), and are interpreted as deposits of a wedge-top depozone under the influence of progressive deformation in the orogenic wedge. The Mishan Formation and overlying Agha Jari mollase-type conglomerates, through interfingering, cover Gachsaran evaporites, paralic sandstones, shales, and calcareous argillites, which in turn overstep the Asmari, Ahwaz, and Kalhur units toward the southwest (fig. 3). In the same manner, the coarse-grained Bakhtiari fluviatile conglomerates and their partly time-equivalent finer-grained Lahbari calcareous argillites and gypsum of more distal facies overlie older strata of megasequence, whose upper limit is defined by the present-day erosional level (fig. 5E).

SUMMARY

Latest Neoproterozoic through Phanerozoic strata (7 – 12 km thick) in the Zagros fold-thrust belt include four groups of rocks that accumulated in different tectonosedimentary environments. They include 11 megasequences, each of which (being progra-

dational or retrogradational or both) represents a specific sedimentary cycle developed in a specific tectonic setting.

1) The lowest megasequence (I) represents deposits of pull-apart basins genetically related to Najd strike-slip tectonism of latest Neoproterozoic to Early Cambrian time. This basal megasequence is overlain by a second megasequence (II), which comprises the transgressive deposits of a shallow epicontinental platform that covered the region during tectonic quiescence in Middle and Late Cambrian time. Overlying the second megasequence, Ordovician, Silurian, and Devonian(?) siliciclastic strata are locally known, but their tectonosedimentary characteristics remain uncertain due to lack of sufficient data.
2) Two megasequences (III and IV) include strata deposited in a warm shallow sea that advanced transgressively over a platform along the margin of Gondwanan landmass during Permian and Triassic time.
3) Four succeeding megasequences (V, VI, VII, VIII), whose facies distributions were partly determined by reactivation of pre-existing structures of the Afro-Arabian continental crust, consist of equatorial shelf deposits along the southern margin of the Neo-Tethyan oceanic realm deposited from earliest Jurassic (Hettangian) to late Cretaceous (Turonian) time.
4) Deposits of a proforeland basin, which formed in front of the Zagros orogen and was progressively incorporated into the orogen between latest Turonian time and the present consist of three megasequences (IX, X, XI) with internal facies variations that represent various proforeland depozones of the basin. The basal proforeland megasequence (IX) evolved as a result of thrust-stacking of Neo-Tethyan ophiolites atop the passive Afro-Arabian continental margin, and the subsequent collision of this margin with the Iranian plates. The middle proforeland megasequence (X) was a response to a reduction of contractional tectonic activity and associated lithospheric unloading by erosion and possibly tectonic denudation in the internal parts of the orogen during Paleocene to Middle Eocene time, followed by renewed southwest-vergent thrust faulting in Middle to Late Eocene time. Finally, the stratigraphic architecture of the uppermost proforeland megasequence (XI) evolved during progressive, southwestward migration of thrust faulting from Oligocene time to the present.

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APPENDIX

Lithostratigraphic Units of the Zagros Fold-thrust Belt of Iran

Available data and information concerning the lithostratigraphic units of the Zagros fold-thrust belt are compiled here after Harrison (1930), Kent (1958, 1979), Falcon (1958), James and Wynd (1965), Wood and Lacassagne (1965), Perry and others (1965), Wells (1967), Dunnington (1967), Perry (1968), Stocklin (1968b, 1986), Player (ms, 1969), Bourgeois (1969), Hart (1970), Sisler (1971), Gill and Ala (1972), Taraz (1974), Kheradpir (1975), Pairaudeau (1976), Ricou (1976), Hallam (1976), Doran (1977), Evers and others (1977), Szabo and Kheradpir (1978), Setudehnia (1978), Elmore and Farrand (1981), Stoneley (1981), Hajmolla-Ali (1989), Alavi and Mahdavi (1994), Shakib (1994), Talbot and Alavi (1996), Ehsanbakhsh (1996), Alavi (1997), Nazari and Shahidi (1998), Karimi-Bavandpour (1999), and Talebian (1999), as well as from unpublished field and laboratory petrographical observations by the author. Geological maps (scale 1: 100,000) of the Consortium Agreement area, published by Oil Service Company of Iran, are also consulted. Sources for the biostratigraphic data include Wynd (1965), Gollesstaneh (ms, 1965; 1974), Adams and Bourgeois (1967), Adams and others (1967), Adams (1969), Khalili (1976), Rahaghi and Schaub (1976), Sissingh (1977), Eshghi (1977), Rahaghi (1984), Ghavidel Syooki (ms, 1988), and Shakib (1990). The sole radiometric age was provided by J. Ramezani (1997, personal communication).

Neoproterozoic to Devonian(?) Pull-apart Basin and Epicontinental Platform Deposits

Hormuz (uppermost Proterozoic to Middle Cambrian): evaporites (mainly halite and anhydrite with subordinate gypsum near top), gray stromatolitic and locally trilobite-bearing dolomite and limestone, and red fluvial siliciclastics (polymict conglomerate, sandstone, siltsone, shale) with interlayered mafic (basalt, basaltic andesite, diabase) and acidic (rhyolite, rhyodacite) volcanics in upper part; includes exotic blocks of gabbro, granitoids (U-Pb zircon age of 547 ± 6 Ma), and metamorphic rocks (slate, phyllite, schist) presumably derived from underlying basement; grades laterally toward the northeast into interbedded dolomite and fissile shale (termed **Soltanieh** in the Zagros imbricate zone).

Barut (Lower Cambrian): thin-bedded gray stromatolitic dolomite interbedded with locally tuffaceous red to purple shale.

Zaigun (Lower Cambrian): variegated (red, purple, gray, green) nonmarine micaceous shale becoming silty and sandy near top.

Lalun (upper Lower Cambrian): cross-bedded fluvial (red and purple) sandstones (arkosic sandstone, quartzose litharenite), siltstone, and shale with polymict pebble conglomerate near top.

Mila (Middle to lower Upper Cambrian): transgressive white orthoquartzite and quartzose sandstone resting disconformably upon Lalun and overlain gradationally by light gray to pink, shallow-marine, trilobite-bearing, partly stromatolitic limestone and dolomitic limestone with thin shale intercalations near top.

Ilbeyk (Upper Cambrian): gray to greenish gray, trilobite-bearing, micaceous marine shale interbedded with thin-bedded siltstone and fine-grained sandstone, and with rare thin intercalations of brachiopod-bearing limestone.

Ordovician strata (including Lower to Middle Ordovician **Zard Kuh**): greenish gray (brown to purple at some horizons) trilobite-bearing and/or brachiopod-bearing, partly graptolitic micaceous shale and thin-bedded litharenite locally rich in volcanic clasts and with intercalations of polymict conglomerate in the southeast (Fars province), and white to light gray, fine-grained quartzose sandstone and quartzarenite with thin carbonate intercalations in the northwest (Lorestan province); basal quartz sandstone (~50 cm thick) overlies Ilbeyk disconformably; overlain unconformably (angular discordance up to ~10 degrees) by basal quartz-pebble conglomerate of Permian Faraghan.

Silurian strata (including "**Gahkum** shales"): unconformity-bounded succession of dark gray to black, *Orthoceras*-bearing and graptolite-bearing, organic-rich (possibly petroleum source) shale and thin sandstone with basal polymict conglomerate layer (nearly 10 m thick) present locally at base.

Devonian(?) strata: unconformity-bounded succession (uncertain age) of light gray to greenish gray, partly conglomeratic sandstone (quartzarenite, arkosic sandstone, litharenite) interbedded with siltstone and shale.

Permian to Triassic Epi-Pangean Platform Deposits

Faraghan (Lower Permian): light gray polymict conglomerate (quartz pebbles up to 5 cm in diameter) overlain by cross-bedded quartzarenite, siltstone, and red shale with thin carbonate intercalations near top; fluvial siliciclastic strata of alluvial-fan and braided-stream origin resting unconformably on older strata and grading upward into transgressively overstepping Dalan carbonates.

Dalan (Lower to Upper Permian): medium- to thick-bedded oolitic to micritic shallow-marine carbonates (dolomite, dolomitic limestone), locally reefal, with intercalations of evaporites (gypsum, anhydrite).

Kangan (Lower Triassic): gray *Claraia*-bearing and partly oolitic, locally vermiculated, limestone and dolomitic limestone becoming first argillaceous (with intercalations of shale) and then evaporitic from southeast to northwest.

Khaneh Kat (Lower to lower Upper Triassic): thin-bedded dark gray (lower part) to brown (upper part) siliceous dolomite and dolomitic limestone with slump and breccia bodies near top; grades toward the southwest into time-equivalent Kangan and Dashtak.

Aghar (medial Triassic): thin interval (~50 m thick) of brown-weathering but locally variegated shale and silty argillite with thin intercalations of dolomite, anhydrite, and siltstone.

Dashtak (Middle to Upper Triassic): massive to thick-bedded, shallow-marine carbonates (dolomite, dolomitic limestone) interbedded with evaporites (anhydrite, gypsum, subordinate halite) and with intercalations of shale and rare siltstone; local disconformities within upper part marked by layers of monomict carbonate-clast conglomerate and increased content of argillaceous impurities.

Jurassic to Upper Cretaceous Continental-shelf Deposits

Neyriz (Lower Jurassic): thin-bedded dolomite and greenish gray shale grading upward to quartzose sandstone (some beds conglomeratic) derived from the northeast, with intercalations of thin argillaceous limestone near top; unconformably onlaps Triassic strata.

Surmeh (Lower to Upper Jurassic): massive gray *Lithiotis*-bearing dolomite and limestone grading upward to marly and silty ammonoid-bearing limestone overlain by cherty dolomite; overlain gradationally by Hith evaporites.

Sargelu (Middle Jurassic; Bajocian to Bathonian): thin interval of dark gray to black, organic-rich papery shale; a possible source for hyrocarbons.

Najmeh (Middle to Upper Jurassic; Callovian to Oxfordian): cyclic alternations of limestones (grainstone, packstone, wackestone, lime-mudstone), in part oolitic and in part pelletal with sponge spicules, interlayered with coarse porous dolomite or dolomitic limestone; disconformably onlaps Sargelu.

Alan/Adaiyah (Upper Jurassic): evaporites (gypsum, anhydrite), interlayered with thin intervals of limestone and shale, gradational laterally and vertically into Hith/Gotnia.

Hith/Gotnia (Upper Jurassic): evaporites (anhydrite, halite) near top of a megasequence (including Sargelu, Najmeh, Alan, Mus, Adaiyah units) deposited during probable extensional reactivation of basement faults.

Fahliyan (uppermost Jurassic–Cretaceous; Tithonian to Hauterivian): massive gray to brown oolitic or pelletal limestone resting disconformably upon Jurassic strata.

Gadvan (Lower Cretaceous; upper Barremian to lower Aptian): grayish green to yellow-brown marl and shale, and associated pelecypod-bearing argillaceous limestone, resting gradationally upon Fahliyan.

Dariyan (Lower Cretaceous; upper Aptian): thick-bedded gray to brown, fine-grained and locally cherty *Orbitolina*-bearing limestone.

Kazhdumi (Lower Cretaceous; Albian): dark, bituminous, ammonoid-bearing limestone, interbedded with dark argillaceous limestone and calcareous shale, overlying Dariyan disconformably; a significant source for hydrocarbons and a distal equivalent of plant-bearing deltaic sandstone and shale of the Burgan Formation in Kuwait and the Nahr Umr Formation in Iraq.

Garau (Lower to Upper Cretaceous; Neocomian to upper Toronian): dark gray to black radiolaria- and ammonoid-bearing shale and argillaceous (locally pyritic) micritic limestone and marl that are sandy and glauconitic near top; deposited on deeper parts of a continental shelf as the lateral equivalent of Gadvan, Kazhdumi, Dariyan, and Sarvak units; probably a significant source for hydrocarbons.

Sarvak (Lower to Upper Cretaceous; upper Albian to upper Turonian): gray, resistant (cliff-forming) shallow-marine limestones (in part argillaceous and micritic and in part sparry) including grainstone, rudist-bearing packstone, and stromatoporoid-bearing wackestone, with thin intercalated intervals of marl grading upward to massive chalky limestone; contains a 30 to 60 meter interval of greenish gray shale.

Upper Cretaceous to Recent Proforeland Basin Deposits

Surgah (Upper Cretaceous; uppermost Turonian to Santonian; includes Laffan shales of Fars province): thin interval (~150 m thick) of dark gray to brown, calcareous and pyritic shale with minor intercalations of thin-bedded calcarenite and micritic limestone; interpreted as the initial deposits of the back-bulge depozone of the proforeland basin.

Ilam (Upper Cretaceous; Santonian to Campanian): thin transgressive interval (150 – 200 m thick) of light gray (locally buff to white) shallow-marine *Hippurites*-bearing limestones (grainstone, pelletal packstone, dark bioclastic wackestone) with intercalations of black fissile shale and broken by several intraformational disconformities; rests unconformably on Surgah and represents forebulge deposits onlapping back-bulge deposits during prograde southwestward migration of proforeland depozones.

Gurpi (Upper Cretaceous; Santonian to Maastrichtian): dark bluish gray, thin-bedded, deep-marine, *Globigerina*-bearing pelagic marl (and marly limestone) and hemipelagic claystone; foredeep facies (resting unconformably on Sarvak and onlapping Ilam) resulting from prograde southwestward migration of proforeland depozones.

Amiran (Upper Cretaceous; Maastrichtian and probably older toward the northeast): dark gray to reddish brown polymict siliciclastics (conglomerate, sandstone, siltstone, shale) composed mainly of ophiolitic detritus (clasts of chert, serpentinite, mafic volcanics and plutonics), as well as limeclasts and recycled conglomerate cobbles; coarsens and thickens, with syndeformational growth strata, toward a provenance to the northeast, and pinches out toward the southwest downlapping Gurpi marls; derived from erosion of ophiolitic complexes "obducted" over the Afro-Arabian continental margin during latest Turonian to Campanian time, and interpreted as the wedge-top depozone of the proforeland basin.

Tarbur (Upper Cretaceous; Maastrichtian): light gray, thick-bedded to massive, locally rudist-bearing and partly reefal, shelly anhydritic limestone with a basal polymict conglomerate (1–2 m thick) in the northeast; unconformably overlies ophiolites and their Amiran erosional products of the wedge-top depozone to the northeast, but to the southwest grades laterally first into deep-marine lime-mudstone and then to Gurpi fine-grained clastics of the foredeep depozone.

Sachun (uppermost Maastrichtian to Paleocene): grayish green *Loftosia*-bearing argillite, red shale, and evaporites (mainly gypsum) deposited in restricted basins and intercalated with thin-bedded dolomite; displays rapid lateral facies changes, becoming richer in siliciclastic strata toward the northeast where it is overlain either by Kashkan conglomerates or by Shahbazan (previously "Jahrum") carbonates, and unconformably downlaps Tarbur carbonates toward the southwest.

Kashkan (Paleocene to middle Eocene): dark reddish brown polymict conglomerate (containing ophiolitic detritus as well as pebbles and cobbles of carbonates, shale, and sandstone) grading progressively toward the southwest to sandstone, siltstone, and finally red shale; a cyclically-deposited, syndeformational, upward-coarsening fluvial siliciclastic wedge (having locally growth stratification) derived from the northeast.

Shahbazan (Eocene): thick-bedded white to brown *Nummulites*-bearing dolomitic limestone, locally sandy and argillaceous, forming a transitional facies between distal Sachun and Kashkan siliciclastics to the northeast and Pabdeh lime-mudstone and argillite to the southwest; includes a narrow belt of dolomite ("Jahrum" locally), as well as the lithologically similar and time-equivalent **Taleh Zang** unit.

Pabdeh (upper Paleocene to lowermost Oligocene): thin-bedded gray and greenish blue (reddish brown near base), *Globigerina*-bearing deep-marine hemipelagic-pelagic calcareous shale, marl, and lime-mudstone with subordinate argillaceous limestone containing fish fossils; foredeep facies grading toward the northeast into sandy Shahbazan dolomitic limestone and toward the southwest into sabhka-type Jahrum carbonates.

Jahrum (Paleocene to upper Eocene): gray (brown-weathering), cliff-forming sabkha-type dolomite interbedded with *Alveolina*-bearing and *Nummulites*-bearing dolomitic limestone; grades toward the northeast into deep-marine Pabdeh foredeep carbonates and toward the southwest to the Radhuma-Rus-Dammam carbonate-evaporite units of Kuwait, Qatar, and Saudi Arabia which pinch out above a regional unconformity.

Ahwaz (medial to Upper Oligocene): well bedded, light gray, wavy-laminated calcarenite interlayered with sandy limestone, sandstones (quartzarenite and litharenite derived from the southwest), and sandy to silty shale; shallow-marine to nonmarine deposits of a sabkha-type environment interpreted as forebulge facies of the basin.

Kalhur (Oligocene, locally lower Miocene): evaporites (gypsum, anhydrite) interbedded with gray calcareous shale, argillaceous limestone, dolomitic limestone, and minor greenish gray marl (near base) deposited within a restricted (narrow and elongate) paralic basin; interfingers toward the northeast with Ahwaz and Asmari, but dies out toward the southwest (into Kuwait and Iraq).

Asmari (Oligocene to lowermost Miocene): medium-bedded to thick-bedded, locally shelly or oolitic, *Nummulites*-bearing limestones (grainstone, packstone, wackestone) shoaling upward above a thin basal conglomerate from fine-grained (low-energy) deep-marine marly limestone to high-energy shallow-marine skeletal grainstone; composed of a number of sequences; an unconformity-bounded, highly prolific reservoir; interpreted as transgressive-regressive foredeep facies of the proforeland basin.

Razak (Oligocene to lower Miocene): variegated (gray, red, green), coarsening-upward siliciclastics (including polymict conglomerate derived from the northeast and pinching out toward the southwest), of highly variable thickness (150 – 1300 + m), interbedded with calcareous argillite and argillaceous limestone; interfingers with and progradationally oversteps Asmari limestones toward the southwest, and also interfingers with lower Gachsaran evaporitic beds to the northeast; deposited in the distal wedge-top depozone of the proforeland basin.

Gachsaran (lower Miocene): multiple sequences of variable thickness and lithology including alternations of gray evaporites (gypsum, anhydrite, subordinate halite), dark bituminous to red shale, gray to red marl, cross-bedded quartzose sandstone (derived from the northeast), and locally conglomeratic calcarenite (to the southeast in Fars province, a thick interval of detrital limestone is termed **Champeh**); interpreted as a distal facies of the wedge-top depozone of the proforeland basin, and progradationally overlaps time-equivalent Jeribe carbonates of southern Iraq toward the southwest; a thick evaporite layer near its base serves as the seal for hydrocarbon reservoirs in the underlying Ahwaz and Asmari units.

Mishan (lower to middle Miocene): gray marl, calcareous shale, siltstone, and sandstone (derived from the northeast) interbedded with ridge-forming ribs of coarse calcarenite and shelly detrital limestone, becoming conglomeratic near top; transitional between distal (partly marine) and proximal (predominantly fluvial) facies of the wedge-top depozone of the proforeland basin; progradationally oversteps Razak and Gachsaran along an unconformable contact, and is overlain gradationally by Agha Jari conglomerates.

Agha Jari (upper Miocene to Pliocene): thick (up to 3000 m) succession (derived from the northeast), mainly marine near its base but paralic to continental at higher horizons, composed of carbonate-clast and polymict conglomerate, calcarenite, gray cross-bedded sandstone (chert grains a major constituent), siltstone, marl, and lime-mudstone (with interlayered lenses of gypsum); displays syndeformational growth strata; multiple upward-coarsening intervals young toward the southwest as proximal facies of the wedge-top depozone of the proforeland basin.

Lahbari (upper Miocene to Pliocene): thick (up to 1560 m) upward-coarsening interval of red to buff, brackish to fresh-water calcareous argillite, siltstone, and cross-bedded limeclast-sandstone containing conglomeratic beds derived from the northeast and interlayered with gypsum lenses; interpreted as a distal facies equivalent of Agha Jari molasse deposited farther to the northeast.

Bakhtiari (Pliocene to Pleistocene): massive to thick-bedded, upward-coarsening fluvial strata (alluvial-fan and braided-stream deposits) composed of polymict conglomerate, cross-bedded sandstone, siltstone, and shale exhibiting rapid lateral changes in facies and thickness including syndeformational growth stratification; interpreted as proximal facies of the wedge-top depozone formed atop the frontal part of southwestward-propagating Zagros thrust sheets, and covered locally by unconsolidated modern alluvial deposits.

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