Review of Middle East Paleozoic plate tectonics

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ABSTRACT

The Paleozoic Middle East terranes, neighboring the present-day Arabian and Levant plates, are shown by most authors to consist of ten major tectonic units: (1 and 2) the Helmand and Farah terranes of Afghanistan, southwest Pakistan and southeast Turkmenistan; (3 to 6) the Alborz, Central Iran (Lut, Yazd and Tabas) and Sanandaj-Sirjan terranes of Iran, and Northwest Iran (possibly extending into eastern Turkey); (7 and 8) the Pontides and Taurides terranes of Turkey; and (9 and 10) the Greater and Lesser Caucasus terranes between the Caspian and Black seas (Armenia, Azerbaijan, Georgia and southwest Russia). Published plate-tectonic reconstructions indicate that all ten terranes may have broken off from either: (1) the Gondwana Supercontinent in the mid-Silurian as part of the Hun Superterrane; or (2) the Pangea Supercontinent during the mid-Permian - Triassic as part of the Cimmeria Superterrane. To the north of Gondwana and Pangea, three successively younger Tethyan oceans evolved: (1) Proto-Tethys (Cambrian - Devonian); (2) Paleo-Tethys (mid-Silurian - Mesozoic); and (3) Neo-Tethys (mid-Permian - Cenozoic).

Two regional Paleozoic unconformities in the Arabian Plate are generally linked to major regional-scale structural events, and commonly correlated to the Caledonian and Hercynian orogenies. These orogenies took place many thousands of kilometers away from the Arabian Plate and are considered unlikely causes for these unconformities. Instead, the breakaway of the Hun and Cimmeria superterranes are considered as alternative near-field tectonic sources. The older unconformity (middle Paleozoic event), represented by a mid-Silurian to Middle Devonian hiatus in North Arabia (Iraq and Syria), reflects an episode of epeirogenic uplift, which might be related to the mid-Silurian rift of the Hun Superterrane. The younger mid-Carboniferous Arabia-wide angular unconformity involved compressional faulting and epeirogenic uplift, and might be related to the earliest phase of subduction by the Paleo-Tethyan crust beneath Cimmeria (Sanandaj-Sirjan and nearby regions) before it broke off. Based on our review and regional considerations, we assign the Helmand, Farah, Central Iran, Alborz, Sanandaj-Sirjan, Northwest Iran, Lesser Caucasus, Taurides and Pontides to Cimmeria, whereas the Greater Caucasus is considered Hunic.

INTRODUCTION

During the past decade, our general knowledge on the geochronological evolution, paleopositions, paleotectonic compositions and paleogeographic outlines of the Phanerozoic supercontinents has significantly improved (e.g. Dalziel, 1997; Stampfli et al., 2001, 2002; Lindsay, 2002; Cocks and Torsvik, 2002; Lawver et al., 2002; Stampfli and Borel, 2002; Veevers, 2003; Pesonen et al., 2003; von Raumer et al., 2002, 2003; Golonka, 2004; Scotese, 2004; Torsvik and Cocks, 2004). Yet today, many uncertainties persist in reconstructing the geological evolution of the regions adjoining the supercontinents, especially for the Paleozoic Era (Cocks and Torsvik, 2002; Torsvik and Cocks, 2004; Scotese, 2004). These regions are in themselves vast, and consist of numerous plate-tectonic units that are sometimes referred to as microplates, terranes, blocks, structural domains, and sometimes grouped into superterranes. The Middle East is a typical example of a border-region that consists of a complex mosaic of tectonic units (Figures 1 and 2).

We identify the Middle East terranes, bordering the present-day Arabian and Levant plates, in Afghanistan, Iran, western Pakistan, Turkey, southeast Turkmenistan and the Caucasus (Armenia, Azerbaijan, Georgia and southwest Russia) (Figures 1 and 2). Several of these terranes are strongly deformed and stacked within a wide tectonic belt between the Eurasian, Arabian and Indian plates.

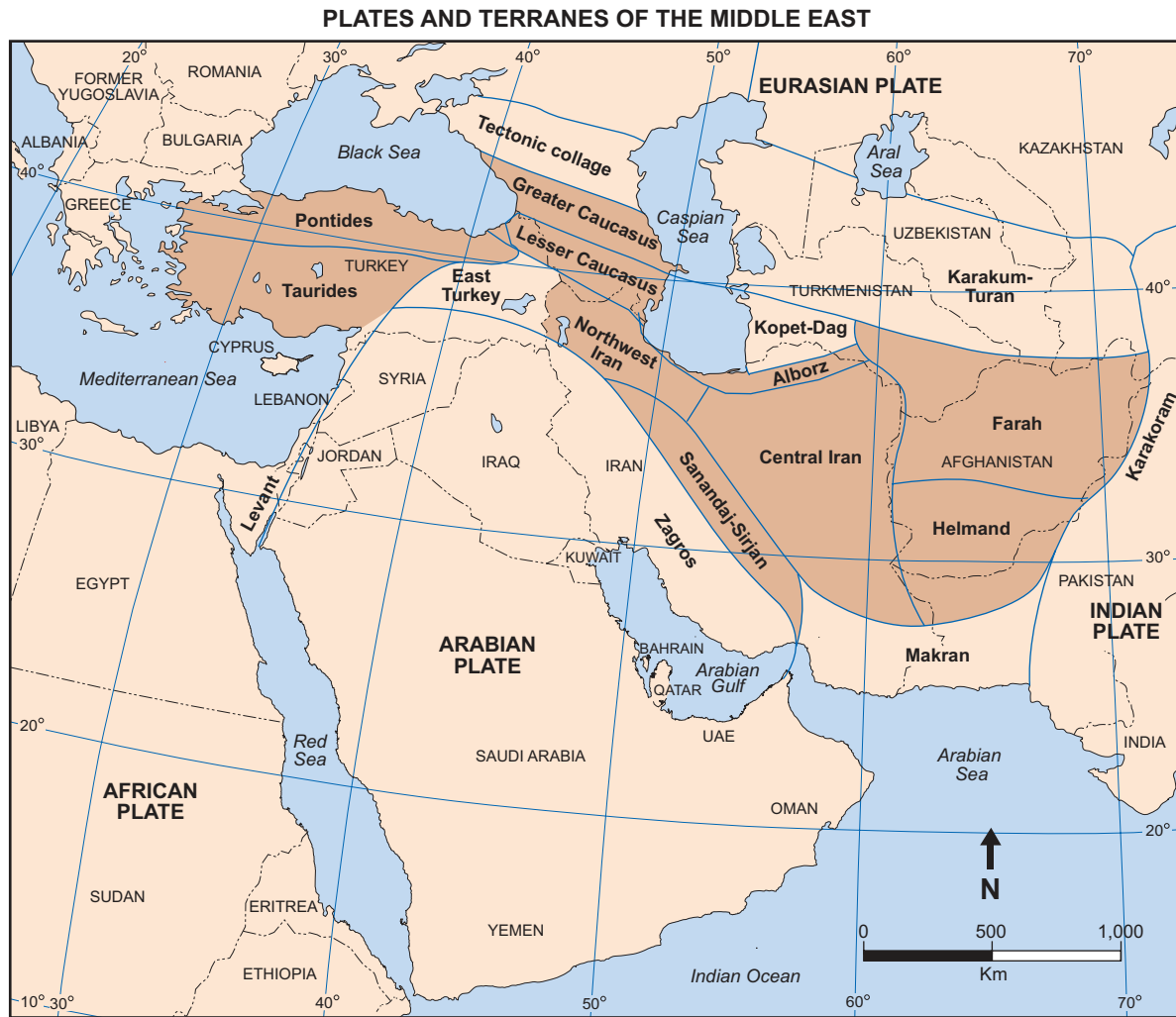**PLATES AND TERRANES OF THE MIDDLE EAST**

Figure 1: The Middle East region consists of the present-day Arabian and Levant plates and numerous terranes (individual boundaries are shown in blue). During the Paleozoic ten large terranes are variably interpreted to have been adjacent to the Arabian and Levant plates (then attached to Gondwana and later Pangea). The Paleozoic Middle East terranes (colored brown) include Helmand and Farah (Afghanistan, southwest Pakistan and southeast Turkmenistan); Iran's Alborz, Northwest Iran, Sanandaj-Sirjan and Central Iran; Turkey's Pontides and Taurides; and the Greater and Lesser Caucasus between the Caspian and Black seas (Armenia, Azerbaijan, Georgia and southwest Russia). The Makran and East Turkey regions may have a Paleozoic core or could have formed as Mesozoic accretionary terranes.

Although their boundaries are generally traced along well-preserved or/and reactivated Paleozoic fault systems, in some cases the borders remain unclear. Correlation of the sedimentary core complexes, however, suggests that all of these terranes share a common ancestry during some time in the Paleozoic Era.

The Middle East terranes were affected by the evolution of the Paleozoic Tethyan oceans, the Hun (Hunic or Intermediate) and Cimmeria (Cimmerian) superterranes, and the Gondwana and Pangea supercontinents (Figures 3 to 11; e.g. Sengör, 1990; Stampfli, 1996; von Raumer, 1998; Cocks and Torsvik, 2002; von Raumer et al., 2002, 2003; Stampfli and Borel, 2002; Stampfli et al., 2001, 2002; Torsvik and Cocks, 2004; Natal'in and Sengör, 2005; Xypolias et al., 2006). At least three major Paleozoic rift episodes occurred along the margins of Gondwana and Pangea (Figures 4 to 11). The first was in the Early Ordovician when Avalonia broke off from Gondwana. This episode was unlikely to have influenced the Middle East region, which was located about 6,000 km away (Figure 4). The second involved the mid-Silurian breakaway of the Hun Superterrane (Figures 6 and 7), the detailed reconstruction of

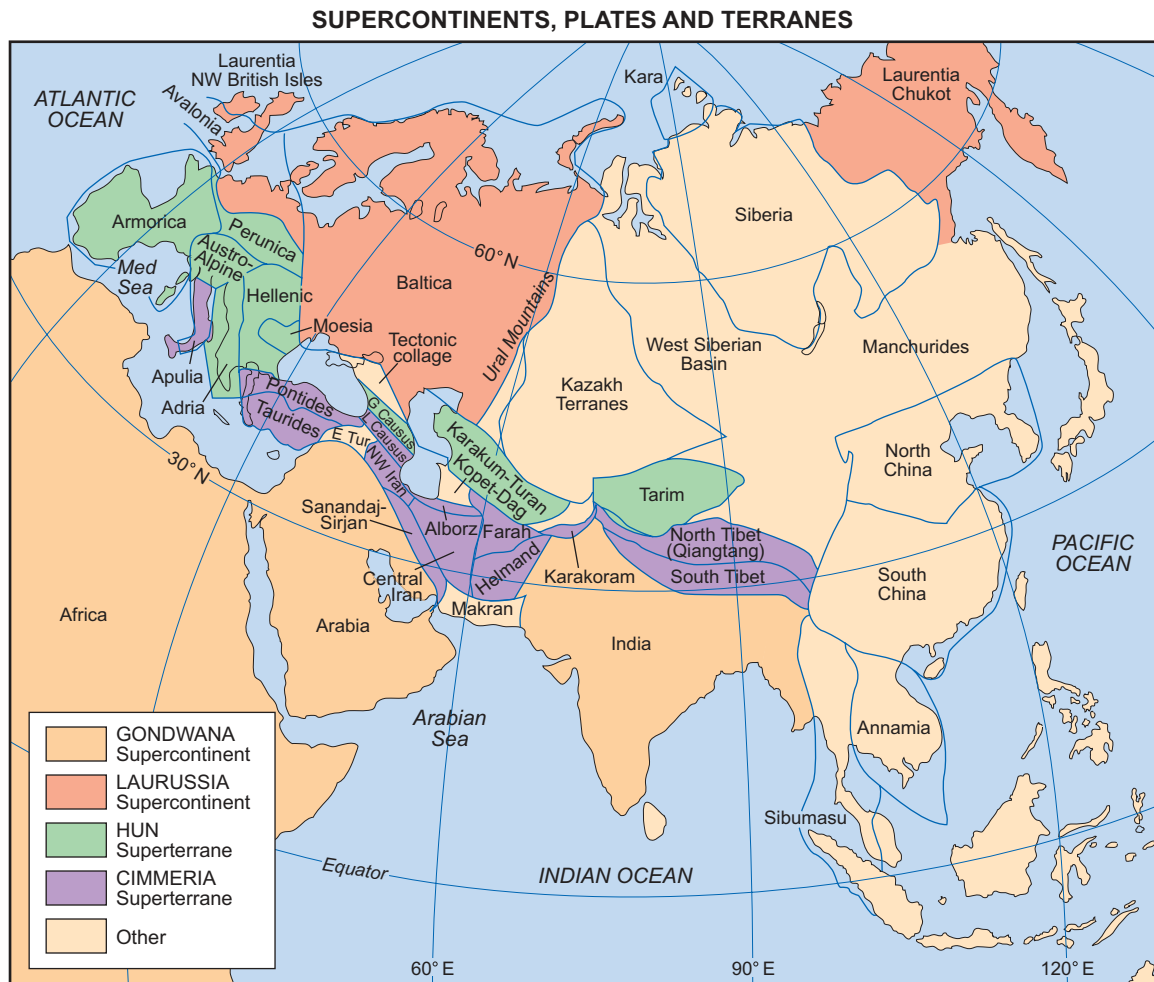**SUPERCONTINENTS, PLATES AND TERRANES**

Figure 2: The majority of the plates and terranes discussed in this review are shown after Torsvik and Cocks (2004). Besides the NW British Isles and the Chukot Peninsula in Russia, the Laurentia Supercontinent included North America and Greenland (see Figures 4 and 5). Laurentia later collided with Baltica and Avalonia to form the Laurussia Supercontinent (Figure 7). Besides Arabia, Africa and India, the Gondwana Supercontinent included Antarctica, Australia and Madagascar (see Figure 4). Also shown are terranes that may have been part of the Hun and Cimmeria Superterranes. Note that Karakoram in north Pakistan is Cimmerian and different from the Hunic Karakum-Turan terrane.

which is unresolved due to insufficient paleomagnetic and paleontological data. This episode is relevant to our review because parts of the superterrane may have involved the Middle East terranes. The third episode is the mid-Permian - Triassic breakaway of several Middle East Cimmerian terranes from Gondwana, by then a part of Pangea (Figures 10 and 11).

In most Paleozoic reconstructions, the Middle East region is interpreted as part of the passive margin of Gondwana and Pangea until the mid-Permian - Triassic, when Cimmeria started to rift away, causing the opening of the Neo-Tethys Ocean (e.g. Sharland et al., 2001; Stampfli et al., 2001). In addition, two regional unconformities are recognized. The first corresponds to a mid-Silurian to Middle Devonian hiatus – "middle Paleozoic hiatus" – that is sometimes correlated with the Caledonian Orogeny (e.g. Buday, 1980) (Figures 3, 5 to 7). The second unconformity represents a "mid-Carboniferous hiatus", and is often correlated to the Hercynian Orogeny (e.g. Berberian and King, 1981) (Figures 3 and 9). These correlations do not provide a satisfactory plate-tectonic model for the Paleozoic evolution of the Middle East region because it was located far away from these two orogenies.

Our paper starts with a brief global review of the largest and relatively well-constrained Paleozoic
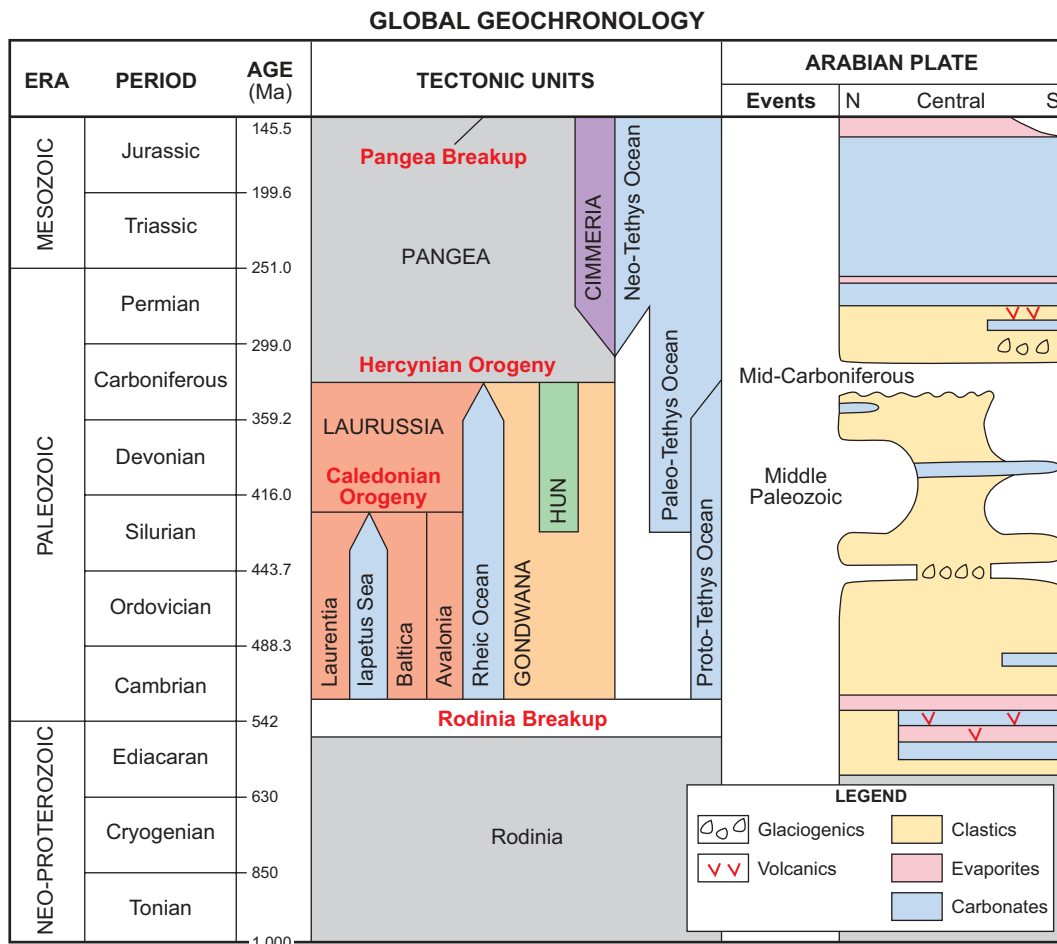
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Figure 3: Simplified geochronology of the supercontinents, superterranes, oceans and seas, and generalized Arabian Plate stratigraphic column. The breakup of the Neo-Proterozoic Rodinia Supercontinent is not discussed in this paper. The geological time scale is after the ICS (International Commission on Stratigraphy; Gradstein et al., 2004). Two Arabian unconformities are associated with Gondwana glaciations: latest Ordovician-early Silurian (Figure 5) and late Carboniferous-early Permian (Figure 9). In Arabia the second glaciation followed a mid-Carboniferous structural event that coincided in time with the Hercynian Orogeny (Figure 9). Another North Arabian (and Oman) unconformity is associated with epeirogenic uplifting in the mid-Silurian (Wenlock) to Middle Devonian (middle Paleozoic event) and has been correlated to the Caledonian Orogeny (Figures 5 to 7). The Hercynian and Caledonian collisions were located many 1,000s of kilometers away from Arabia and could not therefore have transmitted significant lateral forces to its crust. Instead two near-field events may have played a more direct role: the breakaway of the Hun Superterrane in mid-Silurian (and possibly Devonian) (Figure 6), and the early compressional evolution of a subduction complex preceeding the breakaway of the Cimmerian Superterrane (Figure 11). Color scheme for tectonic units follows Figure 2.

plate-tectonic units and seaways. We adopt the conventions of the ICS (International Commission on Stratigraphy; Gradstein et al., 2004) by not capitalizing informal qualifiers "late, middle, mid, early, etc." except where defined (Ordovician and Devonian). After setting the global stage, we discuss the smaller and less constrained units of the Middle East, many of which have unfamiliar names and interpretations. Most of the illustrated global reconstructions follow Cocks and Torsvik (2002) and Torsvik and Cocks (2004), as the involved units are adequately represented. We have also considered the global reconstructions by von Raumer (1998), Stampfli and Borel (2002), von Raumer et al. (2002, 2003), Stampfli et al. (2001, 2002), Scotese (2004), Natal'in and Sengör (2005) and others. Our principal objective is to present the Paleozoic plate-tectonic framework and nomenclature for the Middle East, which can form a basis for further refinements.

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GLOBAL PALEOZOIC PLATE-TECTONIC SETTING

Gondwana, Laurussia and Pangea Supercontinents

The global plate-tectonic configuration during the Paleozoic was dominated by three supercontinents: Gondwana, Laurussia and Pangea. Gondwana, the largest supercontinent on Earth from the Late Cambrian to mid-Carboniferous (Figures 2 to 8), consisted of several present-day plates including Arabia, Africa, most of Antarctica and Australia, India, Madagascar and most of South America, with numerous small terranes attached to their margins (Courjault-Radé et al., 1992; Cocks, 2001; Stampfli et al., 2001; Cocks and Torsvik, 2002; Stampfli and Borel, 2002; von Raumer et al., 2002, 2003; Fortey and Cocks, 2003; Scotese, 2004; Avigad et al., 2005).

During the Paleozoic Era, Laurussia was assembled out of three large plates (Avalonia, Baltica and Laurentia, Figures 3 and 5) and several island arcs in a series of orogenic phases (McKerrow et al., 2000; Stampfli and Borel, 2002; Scotese, 2004) (Figures 3 to 7). The collisional assembly of Laurussia caused the Caledonian Orogeny, an event that was redefined by McKerrow et al. (2000) to apply to the closure of the Iapetus Sea (Figures 3, 5 to 7).

- Avalonia consisted of easternmost North America and parts of northwest Europe (Figures 2 and 3; also Avalonian-Cadomian Arc and Orogenic Belt of Linnemann et al., 2000, and Linnemann and Romer, 2002). Avalonia rifted from western Africa (in Gondwana) in the Early Ordovician (Cocks and Torsvik, 2002), and then drifted northwards until it collided with Baltica and Laurentia (Figures 4 to 7).

- Baltica consisted of the Russian Platform and extended to east of the Ural Mountains (Figures 2 and 3, Cocks and Torsvik, 2002).

- Laurentia consisted of most of North America, Chukot Peninsula of eastern Siberia, Greenland, Spitsbergen and the NW British isles (Figures 3 to 5; Cocks and Torsvik, 2002).

Gondwana and Laurussia remained separated by the Rheic Ocean until the mid-Carboniferous (c. 325–310 Ma) when they collided during the Hercynian Orogeny to form the Pangea Supercontinent (Stampfli and Borel, 2002; Scotese, 2004; Figures 3, 8 and 9, Torsvik and Cocks, 2004). In the late Carboniferous (Pennsylvanian) and Permian, Pangea was enlarged with the amalgamation of the Kazakh, Siberia, Kara and other terranes (Figure 10). The combination of Laurussia with these terranes would later in the Mesozoic form the Laurasia Supercontinent, a term that is easily confused with Laurussia.

Three Tethyan Oceans

The names of the Paleozoic oceans that separated the supercontinents are not unique and vary to reflect somewhat different interpretations. The seaway that opened to the north of the Paleozoic Middle East terranes is called the Paleo-Tethys Ocean by some authors (e.g. Sharland et al., 2001; Bykadorov et al., 2003). Others refer to it as the Proto-Tethys (or Asiatic Ocean) and reserve the term "Paleo-Tethys" for the ocean that opened in the mid-Silurian along the trailing edge of the Hun Superterrane (Figures 3, 7 and 8; e.g. Ziegler et al., 2001; Stampfli et al., 2001; Stampfli and Borel, 2002; von Raumer et al., 2002, 2003). Most authors adopt the Neo-Tethys for the ocean that opened in mid-Permian - Triassic along the African-Arabian margin of Gondwana (e.g. Stampfli and Borel 2002; also Meso-Tethys of Metcalfe, 1999; Pindos Ocean of Golonka, 2004; Figure 10). Following Stampfli and Borel (2002), we adopt Proto-Tethys for the early Paleozoic ocean to distinguish it from the late Paleozoic Paleo-Tethys and Neo-Tethys oceans (Figures 3–10).

The interpretation of the lateral extent and evolution of the Tethyan oceans can vary. Hünecke (2006), for example, argued that the Middle-Late Devonian ocean between Gondwana and Laurussia was not as large as depicted by Stampfli and Borel (2002) and Torsvik and Cocks (2004). Stampfli and Borel (2002) and von Raumer et al. (2002, 2003) interpreted that in the Late Ordovician-early Silurian, the eastern branch of the Proto-Tethys Ocean might have closed when Serindia terranes (North China and
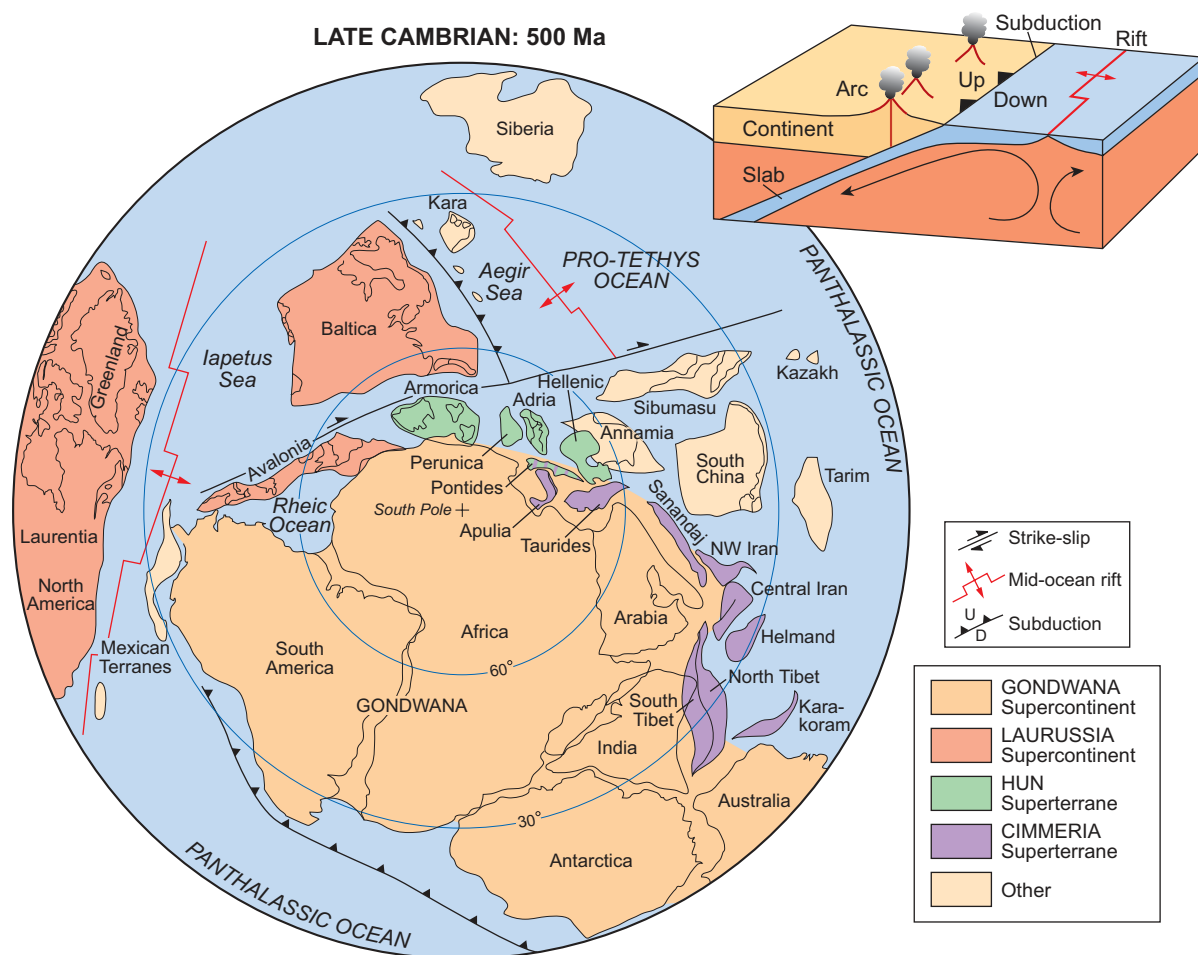
Figure 4: Plate-tectonic reconstruction of the Late Cambrian times (modified after Cocks and Torsvik, 2002). The terranes included in the Hun Superterrane (green) are mostly after Stampfli et al. (2001, see Figure 6). Torsvik and Cocks (2004) show several terranes breaking away from Gondwana in the middle Paleozoic but do not appear to recognize the Hun Superterrane (Figure 7). The Adria terrane (Figures 6 to 9, after Torsvik and Cocks, 2004) was not shown in Cocks and Torsvik (2002) and is located arbitrarily in Figures 4 and 5. Middle East terranes (Figures 1 and 2) not shown are Alborz, Farah and Caucasus. Pontides shown as Hunic by Cocks and Torsvik (2002), but considered Cimmerian in our paper (in stripes). Schematic diagram at top right illustrates oceanic slab subducting below (down or D) the continent (up or U).

Tarim) amalgamated with Gondwana. Several authors interpreted the initial opening of the Neo-Tethys Ocean in early rather than mid-Permian (Vannay, 1993; Garzanti and Sciunnach, 1997; Garzanti et al., 1994, 1996a, b, 1999; Stampfli and Borel, 2002; Angiolini et al., 2003), or to have started north of Australia in the Carboniferous and extended diachronously westwards into the Permian (Stampfli, 2000).

Iapetus Sea and Rheic Ocean

Two more Paleozoic seaways are significant for our review (Figures 3 to 7). The Iapetus Sea, which separated Laurentia, Avalonia and Baltica in the early Paleozoic, closed in the late Silurian when these terranes joined to form Laurussia (Figures 3 to 5). The Rheic Ocean (also Rheic-Mauritania, Rhenohercynian or Hercynian-Rheic) opened in the Cambrian along Avalonia's northerly trailing edge (Figures 3 to 7). During the Devonian-early Carboniferous (c. 420–320 Ma), Gondwana drifted towards Laurussia, closing the Rheic Ocean (Figures 7 and 8, Torsvik and Cocks, 2004). In the mid-Carboniferous, the Hercynian Orogeny occurred along a front between northwest Africa and southeast North America and closed the Rheic Ocean (Figure 9; incorrectly referred to as the Iapetus Sea in Al-Husseini, 2004).

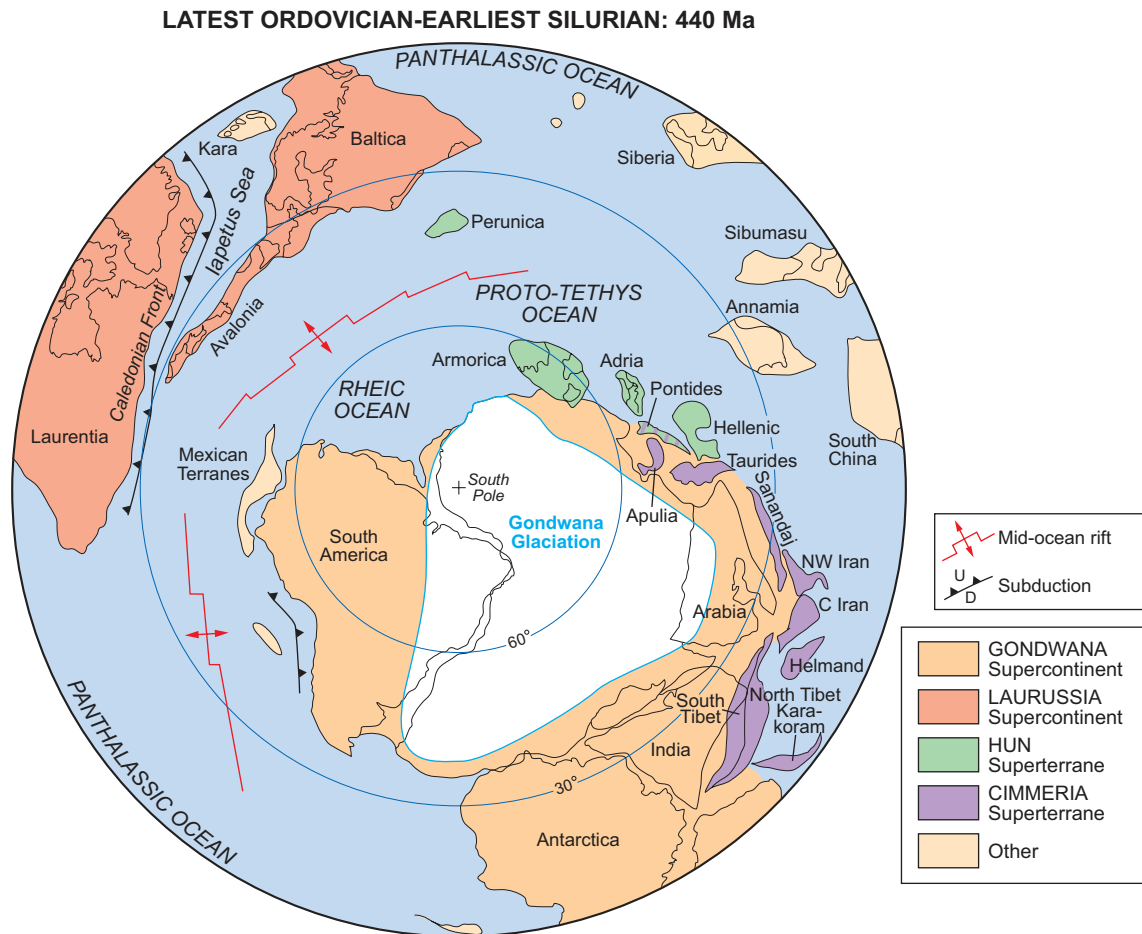**LATEST ORDOVICIAN-EARLIEST SILURIAN: 440 Ma**

Figure 5: Plate-tectonic reconstruction of the latest Ordovician-earliest Silurian times (modified after Cocks and Torsvik, 2002). During the final Hirnantian Stage of the Late Ordovician, polar glaciers advanced over regions of Gondwana reaching western Saudi Arabia (Vaslet, 1990). Baltica and Avalonia were joined, closing the Iapetus Sea where the Caledonian Orogenic Front was located. Middle East terranes (Figures 1 and 2) not shown are Alborz, Farah and Caucasus. Adria terrane is located arbitrarily (see Figure 4 caption). Pontides shown as Hunic by Torsvik and Cocks (2004), but considered Cimmerian in our paper (in stripes).

Hun Superterrane

Plate reconstruction of the mid-Silurian to mid-Permian northern margin of Gondwana fall into two general models (Figures 6 and 7). Whereas both show the breakaway of various terranes from Gondwana, they differ in detail and lateral extent – particularly near the Middle East region.

In the first model, following Stampfli et al. (2001) and Stampfli and Borel (2002), the ribbon-like Hun Superterrane extended from westernmost Iberia (in Spain) to Qiantang (Figure 6). This superterrane is also referred to as the Hun Composite Superterrane because it is divided into (Figure 6): (1) the northern Hun Cordillera terranes (also European Hunic terranes); and (2) the southern Hun Gondwana terranes (also Asiatic Hunic terranes) (von Raumer, 1998; Stampfli et al., 2001; von Raumer et al., 2002, 2003; Stampfli and Borel, 2002; Schulz et al., 2004). This division reflects the separate evolution of the two sets of terranes after they docked along Laurussia in the late Paleozoic. The Hun Superterrane rifted away from Gondwana in the mid-Silurian (possibly in different phases that lasted into the Devonian) and then drifted towards Laurussia, with which it collided in the Devonian-Carboniferous (Figures 3, 6 to 8). Interpretations of late Silurian paleocurrents indicate that the Panthalassic (north of the Proto-Tethys) waters did not mix with those of the Paleo-Tethys (Johnson et al., 2004), thus suggesting that the Hun Superterrane remained consolidated until at least the Early Devonian.
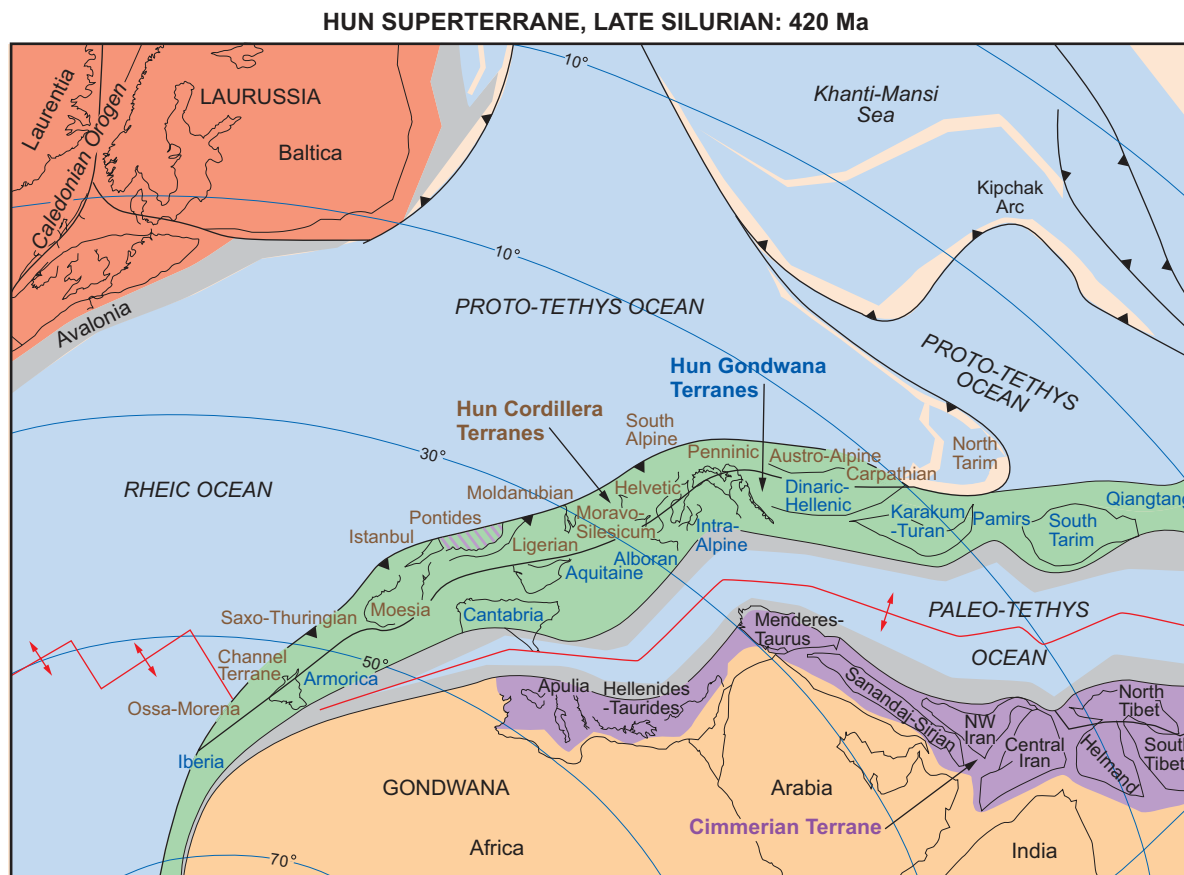
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HUN SUPERTERRANE, LATE SILURIAN: 420 Ma

Figure 6: Plate-tectonic reconstruction of the late Silurian (Ludlow) by Stampfli et al. (2001) shows the Hun Superterrane rifting away from the Gondwana Supercontinent. The Paleo-Tethys Ocean formed between Gondwana and the superterrane. The superterrane is divided into the southern Gondwana and northern Cordillera terranes. Stampfli et al. positioned the Istanbul and Pontides terranes (North Turkey) near a subduction zone at the northern boundary of the Hun Cordillera terrane. In contrast, Sengör (1990; see Figure 11) placed the Pontides (in stripes) in the Cimmeria Superterrane and associated it with a middle Carboniferous-Mesozoic subduction-arc that continued into the Sanandaj-Sirjan terrane. Middle East terranes (Figures 1 and 2) not shown are Cimmerian Alborz, Farah and Lesser Caucasus. The Hunic Greater Caucasus may have been located further east beyond Qiangtang.

From west to east the Hun Cordillera terranes included: Ossa-Morena, Channel, Saxo-Thuringian, Moesia, Istanbul, Pontides, Ligerian, Moldanubian, Moravo-Silesicum, Helvetic, South Alpine, Penninic, Austro-Alpine, Carpathian and North Tarim (Figure 6; Stampfli et al., 2001). The Hun Gondwana terranes included: Iberia, Armorica, Cantabria, Aquitaine, Alboran, Intra-Alpine terranes (Adria, Carnic, Austro-Carpathian), Dinaric-Hellenic, Karakum-Turan, Pamirs, South Tarim, Qiangtang, North and South China, and Annamia terranes (Stampfli et al., 2001; Stampfli and Borel, 2002; the latter two easternmost terranes are shown in Figure 1, but not in Figure 6). In the Devonian, the Kazakh terranes may also have been close to the Hunic Cordillera Superterranes (Stampfli and Borel, 2002). The remaining adjoined with Pangea were Apulia, Hellenides-Taurides, Menderes-Taurus, Sanandaj-Sirjan, Northwest and Central Iran, Helmand, North and South Tibet.

In the second model, several terranes broke off and had drifted some distance away from the northwestern margin of Gondwana by the Early Devonian (Figure 7; Torsvik and Cocks, 2004). They also formed a ribbon-like superterrane that vaguely resembles the western part of the Hun Superterrane (compare Figures 6 and 7). The breakaway group included: Rheno-Hercynian, Armorica (includes Iberia), Adria, Pontides, Hellenic and Moesia (Figures 2 and 6). The Rheno-Hercynian and Perunica
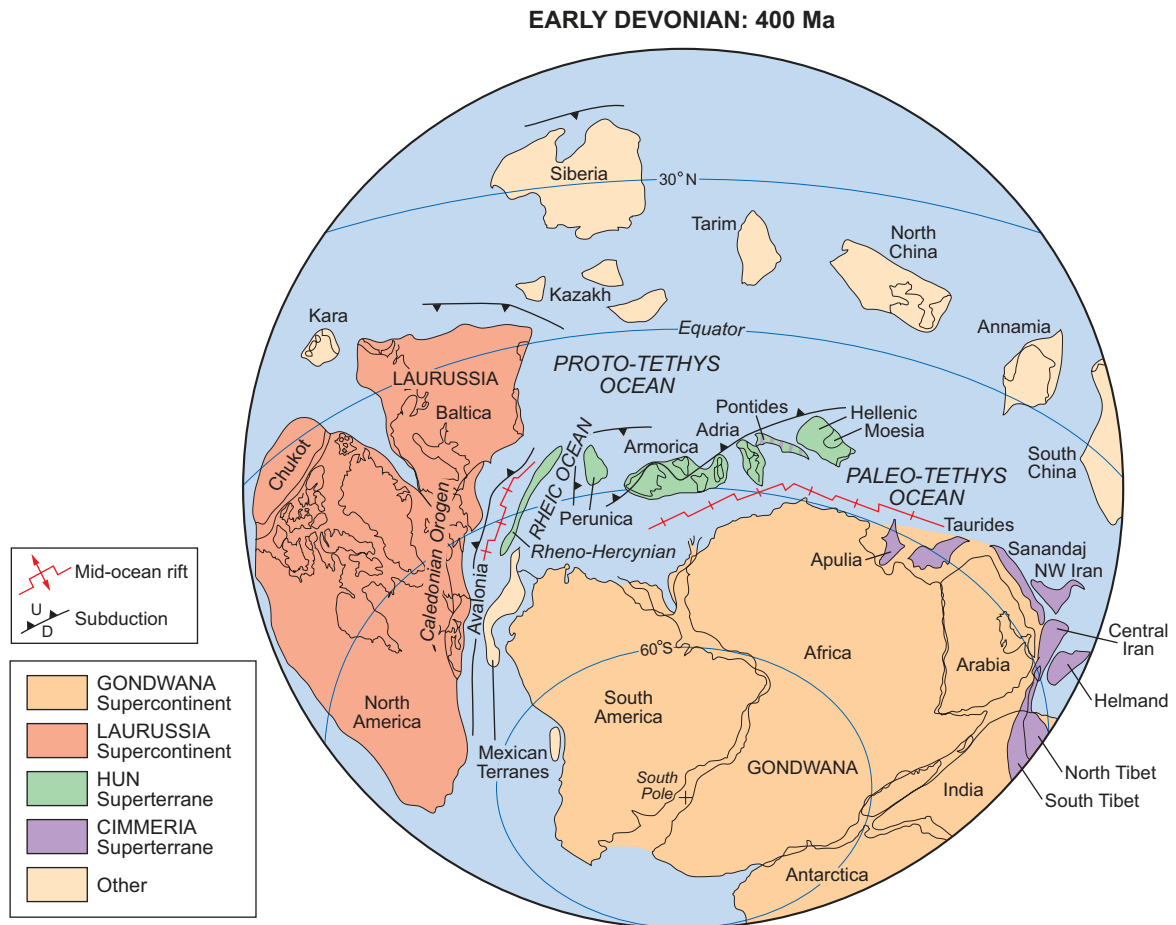
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Figure 7: Plate-tectonic reconstruction of the Early Devonian (modified after Torsvik and Cocks, 2004) shows the breakaway from Gondwana of several terranes that together resemble the western Hun Superterrane (Stampfli et al., 2001; Figure 6). Both reconstructions show the Pontides (in stripes) as Hunic whereas we favor a Cimmerian assignment. Middle East terranes (Figures 1 and 2) not shown are Hunic Greater Caucasus and Cimmerian Alborz, Farah and Lesser Caucasus. Note that North Tibet and Qiangtang are synonyms in Torsvik and Cocks, but two different terranes in Stampfli et al.

are considered as separate terrane between the Hunic terranes and Baltica (in Laurussia) (Kríz et al., 2003; Torsvik and Cocks, 2004). Following the breakaway event, terranes adjacent to Gondwana were Apulia, Taurides, Sanandaj-Sirjan, Northwest and Central Iran, Helmand, South Tibet (Lhasa) and North Tibet (Qiangtang) terranes.

Some differences and confusion occur when comparing the two models in detail. The term Qiangtang (also Qangtang) is a synonym for North Tibet in Torsvik and Cocks (2004; Figure 2) and positioned next to South Tibet (Lhasa). In contrast, Stampfli et al. (2001) show Qiangtang as Hunic but North Tibet as Gondwanan (Figure 6). Other confusing terms are Karakum and Karakoram (also spelled as Karakorum). Karakum and neighboring Mangyshlak of Torsvik and Cocks (2004) are equivalent to the Karakum-Turan terrane (Figure 1). Karakum-Turan was not attached to Gondwana in the late Paleozoic (L. Angiolini, written communication, 2006) and probably Hunic (Figure 6). Karakoram is located in northern Pakistan (Gaetani, 1997; Figure 1), which belonged to Cimmeria (L. Angiolini, written communication, 2006). Further studies of the Cambrian-Ordovician rocks in Karakorum, based on the works of Gaetani et al. (1996), Gaetani (1997), Quintavalle et al. (2000) and Rolland et al. (2002), may provide new insights for its early Paleozoic paleoposition. Turan is often mentioned as a plate, but the Russian term 'plate' differs in meaning from 'tectonic plate', causing some further confusion (Laz'ko, 1975). It remains unclear whether Karakum and Turan formed one or several terranes.
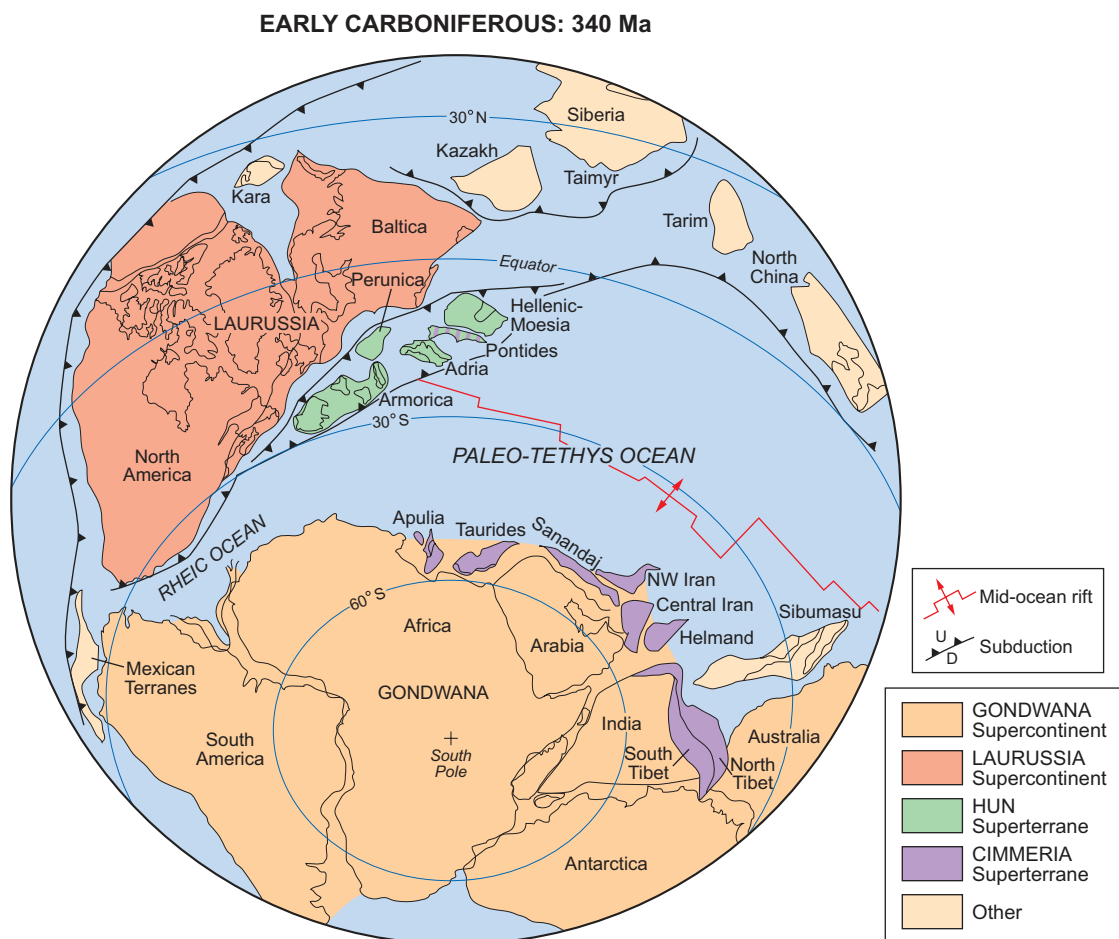
EARLY CARBONIFEROUS: 340 Ma

Figure 8: Plate-tectonic reconstruction of the early Carboniferous (Mississippian) (modified after Torsvik and Cocks, 2004). The Hun Superterrane had closed the Proto-Tethys Ocean and the Rheic Ocean was closing as Gondwana and Laurussia drifted towards each other. Middle East terranes (Figures 1 and 2) not shown are Hunic Greater Caucasus and Cimmerian Alborz, Farah and Lesser Caucasus. Pontides shown as Hunic by Torsvik and Cocks (2004), but considered Cimmerian in our paper (in stripes).

Cimmeria Superterrane

In the mid-Permian - Triassic, Cimmeria started rifting away from Pangea and closing the Paleo-Tethys Ocean to the north, while opening the Neo-Tethys Ocean in its wake (Figure 10). Less clear is which terranes were Cimmerian, or Hunic or possibly neither. Torsvik and Cocks (2004, Figure 10) show Cimmeria to consist of Apulia, Taurides, Sanandaj-Sirjan, Northwest and Central Iran, Helmand and North Tibet (Qiantang). They place South Tibet (Lhasa) to the north of India, however noting that it is not constrained by paleomagnetic or faunal content. Stampfli et al. (2001) and Stampfli and Borel (2002) (Figures 1, 2 and 6) included in Cimmeria: Apulia, Hellenides-Taurides, Menderes-Taurus, Sanandaj-Sirjan, Northwest and Central Iran, Helmand, South and North Tibet. A comparison indicates that several Middle East terranes (Northwest and Central Iran, Taurides and Sanandaj-Sirjan) are considered Cimmerian by both groups of authors.

In contrast to the somewhat generalized Cimmeria of some authors (e.g. Sharland et al., 2001; Stampfli et al., 2001; Stampfli and Borel, 2002; Torsvik and Cocks, 2004), Sengör (1990, Figure 11) showed the Cimmeria breakaway event in substantial detail and to consist of three ribbons. He divided North Tibet into East and West Qiangtang and considered the former as the leading Cimmerian ribbon. The "Intermediate" ribbon consisted of East Pontides, Dzirula Massif, Artvin/Karabagh, Sanadaj-Sirjan, Northwest Iran (including Alborz), Central Iran (Yazd, Tabas, and Lut), Farah, central Pamirs (China) and West Qiangtang. The trailing third ribbon included Helmand and South Tibet. The latter two

ribbons connected to Australia, and the Neo-Tethys Ocean consisted of several seaways. Significantly for our paper, Sengör's model intepreted a subduction zone along the northeast front of Sanandaj-Sirjan and other northerly terranes, a subject that will be discussed later. The Intermediate ribbon of Natal'in and Sengör (2005) is generally comparable with the Cimmerian Superterrane.

PALEOZOIC OROGENIES AND THE ARABIAN PLATE

In most of the pre-Permian Paleozoic reconstructions (Figures 4 to 9), the Arabian Plate is generally depicted inland from the Tethyan margins of Gondwana, or later Pangea. Until the mid-Permian (Figures 10 and 11), it is shown as bounded by the Middle East terranes and, for the most part, at latitudes of about 30° to 60° south. Two regional hiatuses that were associated with polar glaciations occurred in the Late Ordovician Hirnantian Stage (Figures 3 and 5; Vaslet, 1990; Abed et al., 1993) and in the late Carboniferous - early Permian (Figures 3 and 9; Osterloff et al., 2004).

Two structurally significant unconformities have been recognized in the Arabian Plate (Figure 3). The mid-Silurian (Wenlock) to Middle Devonian hiatus is regionally manifested in Syria and Iraq, and possibly other parts of the Middle East (Brew and Barazangi, 2001; Al-Hadidy, 2007). Because of its age, it was correlated to the Caledonian Orogeny by some authors (e.g. Buday, 1980). In southeast Arabia (Oman), distinct hiatuses occur in the mid-Silurian (Wenlock) to earliest Devonian, and in the Middle Devonian to mid-Carboniferous (Millson et al., 1996; Droste, 1997; Osterloff et al., 2004). It would therefore appear that parts of Arabia could have been uplifted as highlands, most probably sometime between the mid-Silurian and Middle Devonian. These highlands may be related to pre-rift thermal swelling or post-rift isostatic rebound associated with the breakaway of the Hun Superterrane (Figure 6), rather than the Caledonian Orogeny (Figure 5).

The mid-Carboniferous unconformity is sometimes correlated to the Hercynian Orogeny, and the term "Hercynian unconformity" is adopted in regional and local studies by numerous authors (e.g. Stöcklin and Setudehnia 1972; Berberian and King, 1981). In Saudi Arabia, the angular pre-Unayzah unconformity correlates to the mid-Carboniferous hiatus (Figure 3, c. 325–310 Ma, Al-Husseini, 2004; at least Serpukhovian, Bashkirian and early Moscovian, Gradstein et al., 2004). The associated differential structural relief is manifested by broad epeirogenic swells (many 100s of kilometers in lateral extent) and laterally extensive (100s of kilometers) upthrown blocks (several 100s of meters), bounded by transpressional to reverse faults (Wender et al., 1998; Al-Husseini, 2004). The Hercynian Orogeny appears to have been too distant to account for the severity and style of this in deformation in Arabia (Figure 8 and 9).

An alternative to correlating the Hercynian Orogeny to the mid-Carboniferous Arabian unconformity is considered in the interpretation shown in Figure 11 of Sengör (1990). This Early Triassic reconstruction shows a SW-oriented subduction zone of the Paleo-Tethys oceanic crust beneath parts of Cimmeria. Next to the subduction complex, the Podataksasi Arc (a name Sengör derived from the initial letters of Pontides, Dzirula, Adzharia-Trialeti, Artvin-Karabagh and Sanandaj-Sirjan; Figure 11) was mainly a Carboniferous episode of orogenic deformation, metamorphism, and arc-type, calk-alkaline magmatism. This interpretation is based on a detailed study of successions in the involved terranes (see Sengör, 1990). Natal'in and Sengör (2005) included the Podataksasi Arc in the so-called Silk Road Arc, which stretched during the late Paleozoic-early Mesozoic from the Caucasus through north Iran and the Pamirs to China.

Further westwards, Xypolias et al. (2006) extended the subduction-arc model from the Pontides to the Hellenic terrane (External Hellenides) and northeast Greece. U-Pb dating of zircon from a granitic orthogneiss in the Kithira Island (southern Greece) yielded a late Carboniferous age of 324–323 Ma. Taken together with other geochronological data from the Aegean region it provides evidence for a restricted period of plutonism between 325–300 Ma (Xypolias et al., 2006). These authors concluded that northeast Greece (Cycladic and Palegonian basements) and northwest Turkey (Menderes Massif in the Taurides terrane and Sakarya Zone in the Pontides terrane) formed part of Cimmeria.

A reviewer (written communication, 2006) noted that a subduction complex does not transmit compressional horizontal stresses across broad regions and, moreover, a SW-directed compression
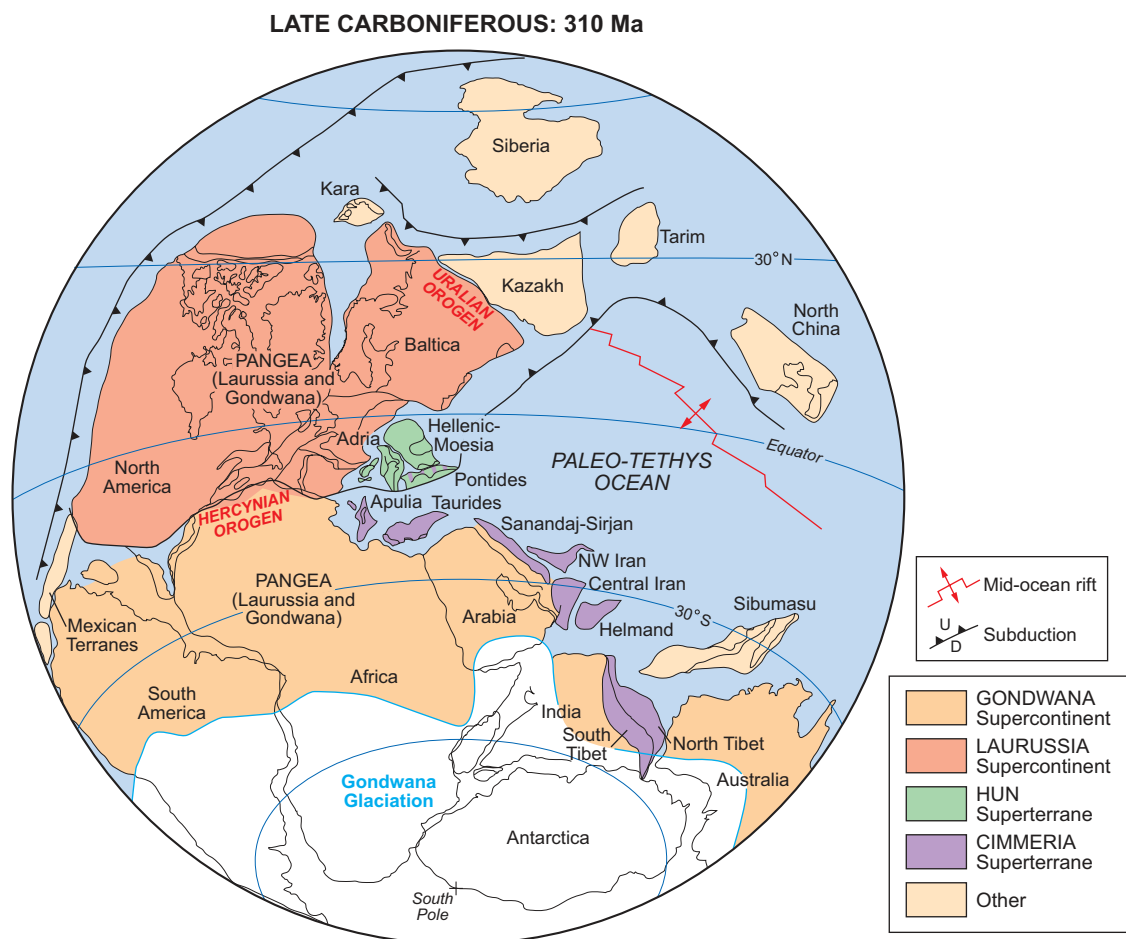
LATE CARBONIFEROUS: 310 Ma

Figure 9: Plate-tectonic reconstruction of the late Carboniferous (Pennsylvanian; modified after Torsvik and Cocks, 2004). In the mid-Carboniferous times, the collision of Gondwana and Laurussia closed the Rheic Ocean causing the Hercynian Orogeny. Also in the late Carboniferous the collision of the Kazakh terranes with Pangea caused the Uralian Orogeny. In the Arabian Plate, an angular mid-Carboniferous unconformity is associated with epeirogenic swells and extensive compressional block faulting and a regional hiatus between about c. 325–310 Ma. The unconformity is widely referred to as "Hercynian" and associated with the Hercynian Orogeny. A more proximal tectonic event that may have caused the deformation of Arabia may have been the initiation of subduction along the Paleo-Tethyan margin of Cimmeria (Figure 11). The late Carboniferous - early Permian Gondwana glaciation extended into southern Arabia. Middle East terranes (Figures 1 and 2) not shown are Hunic Greater Caucasus and Cimmerian Alborz, Farah and Lesser Caucasus. Pontides shown as Hunic by Torsvik and Cocks (2004), but considered Cimmerian in our paper (in stripes).

appears inconsistent with the NS-trending grain of the fault-bounded Arabian structures. He pointed out that the initiation of subduction is commonly associated with a strong pulse of trench suction leading to roll-back, both processes exerting a strong extensional pull on the continental margin overlying the evolving subduction zone. As an analog to the Hercynian Orogeny's influence in Arabia, he suggested the present-day Indian Plate. It is piercing into the anisotropic assembly of Central South Asia, with its effect reaching even the distant east coast of Asia. He concluded that a far-field relationship to Hercynian orogenic forces still cannot be completely excluded in Arabia.

Besides the data supporting a compressional mid-Carboniferous pulse due to a subduction-arc complex (Sengör, 1990, Figure 11; Xypolias et al., 2006), the concerns raised by the reviewer can be addressed. Whereas subduction complexes are indeed driven by slab-pull and associated with back-arc extension in the continental margin, this regime develops after an initial compressional stage. The pre-subduction stage involves first rupturing the entire oceanic crust (10 or more kilometers thick) and initiating
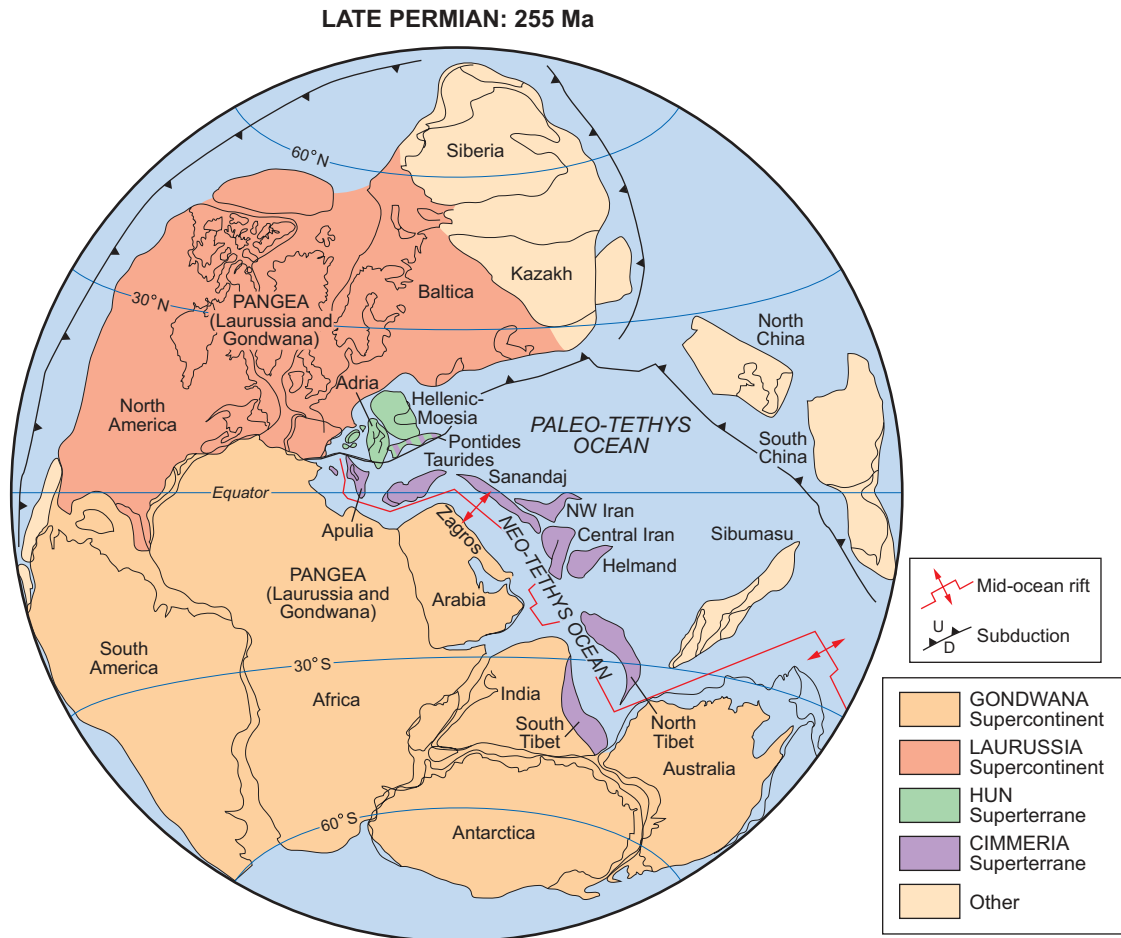
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LATE PERMIAN: 255 Ma

Figure 10: Plate-tectonic reconstruction of the late Permian (Lopingian) time (modified after Torsvik and Cocks, 2004). In the mid-Permian - Triassic the Cimmeria Superterrane broke away from Gondwana, now part of the Pangea Supercontinent (Gondwana and Laurussia supercontinents, as well as Kazakh, Siberia and other terranes). Middle East terranes (Figures 1 and 2) not shown are Hunic Greater Caucasus and Cimmerian Alborz, Farah and Lesser Caucasus. Pontides shown as Hunic by Torsvik and Cocks (2004), but considered Cimmerian in our paper (in stripes).

subduction along a new thrust zone. The horizontal forces required to fracture the brittle crust, then bend and push down the oceanic plate are not only compressional but of regional significance. In some cases, the thrust geometry is reversed and the compressional force is great enough to push the oceanic crust above the continental margin resulting in an obduction. It is considered here that the mid-Carboniferous event was an early pre-subduction compressional phase, while the mid-Permian - Triassic was the extensional one.

The relationship between a SW-directed compression and the NS-trending Arabian uplifted fault blocks was one of mid-Carboniferous transpression along pre-existing NS-oriented fault systems. The Arabian basement manifests a fault system with a NS-, NE- and NW-trending grain that was established in the late Proterozoic and Early Cambrian (Al-Husseini, 2000, 2004). We argue that a SW-directed compressional pulse would have caused the pre-existing Arabian basement-cored structures to be dislocated in a right-lateral transpressional style.

In summary, it seems likely that two regional angular unconformities in the Arabian Plate were related to plate-tectonic events that occurred in the vicinity of the Middle East terranes. The mid-Silurian to Middle Devonian unconformity (middle Paleozoic event instead of Caledonian Orogeny) may have involved the uplift of the northern Arabia margin (and Oman) in Gondwana. The uplift may have occurred along the newly formed Paleo-Tethys Ocean prior to, during or possibly after the breakaway

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of the Hun Superterrane. The mid-Carboniferous unconformity (instead of Hercynian unconformity) may have resulted from deformation caused by a compressional subduction-initiation phase along the outer margin of Cimmeria before it broke off in the Middle Permian-Triassic.

DISCUSSION OF THE MIDDLE EAST TERRANES

In this section, we discuss the various plate-tectonic interpretations of the individual Middle East terranes (Figures 1 and 2). We highlight conflicting interpretations and suggest preferred interpretations where data and regional considerations allow. The terrane-by-terrane sections follow from present-day northwest to southeast (Figure 1).

The Pontides and Taurides Terranes

Turkey (Figure 1) presently occupies the active collision zone between the Arabian and Eurasian plates (Bird, 2003), and interpretations of its Paleozoic history vary from a single terrane to several. Scotese (2004) positioned Turkey next to the Levant and Egypt (Figures 1 and 2) throughout the Paleozoic and early Mesozoic, and in the Cretaceous showed it drifting northwards until it collided with Eurasia in the middle Cenozoic (c. 30 Ma). Similar single-terrane models involving only Mesozoic rifting were adopted by others (e.g. Grabowski and Norton, 1995; Sharland et al., 2001).

Göncüöglü and Kozlu (2000) separated Turkey into the northern Pontides and southern Taurides by a Paleozoic ocean that closed in the Carboniferous. They correlated post-collisional granitoids and suggested that the Taurides was originally Gondwanan. As discussed earlier, Sengör (1990, Figure 11) considered the Pontides (and Kersehir) and Taurides (Menderes-Taurus) terranes to be parts of two Cimmerian ribbons with the intervening Neo-Tethys (Inner Taurides) Ocean.

Several authors, however, interpreted the Pontides as Hunic and the Taurides as Cimmerian (Figures 6 and 7; Stampfli et al., 2001; Cocks and Torsvik, 2002). Moreover, based on a detailed analysis of foraminiferal paleobiogeography and plate tectonic review, Kalvoda (2002) concluded that Turkey was Laurussian, rather than Gondwanan. An investigation of the Carboniferous (Viséan) foraminiferal and algal paleobiogeography suggests that the Taurides was located along the northwestern border of the Paleo-Tethys (Okuyucu and Vachard, 2006).

Therefore it appears that the Paleozoic paleopositions of the main Pontides and Taurides terranes of Turkey remain unresolved in the literature. As discussed above, we favor the interpretation of these two terranes as Cimmerian and specifically within the regional context of the mid-Carboniferous subduction-arc complex (Figure 11, Sengör, 1990; Xypolias et al., 2006).

The Caucasian Terranes

The Greater Caucasus terrane is presently located south of the Russian Platform (Gamkrelidze, 1997; Tawadros et al., 2006) (Figures 1 and 2, i.e. Baltica), and its Paleozoic sedimentary complexes crop out in the central Greater Caucasus Mountains (Ruban, 2006). Paleontological data from Silurian (Ludlow) carbonates (bivalve and ammonoid assemblages, Bogolepova, 1997), Pennsylvanian paleobotanical data (Anisimova, 1979), and middle and upper Paleozoic paleomagnetic data (Shevljagin, 1986) suggest that the Greater Caucasus was not a part of Baltica, as traditionally proposed (e.g. Laz'ko, 1975; Bykadorov et al., 2003). The faunal and floral assemblages, as well as the lithostratigraphic architecture, are similar to those of Hunic Perunica and Carnic Alps (Central and Alpine Europe, Figures 2 and 7). Moreover, its lower Silurian mainly clastic and volcaniclastic succession resembles that of the Hunic margin of the Paleo-Tethys.

In the Middle-Late Devonian (until Famennian) about 4,500 m of mixed volcaniclastics and volcanic rocks were deposited in the Greater Caucasus (Kizeval'ter and Robinson, 1973). The volcanic activity may have been due to tectonism between the Greater Caucasus and other Hunic terranes. Alternatively, the magmatic activity may have been associated with the closure of the Rheic Ocean (Stampfli and Borel, 2002; Figure 6). We therefore follow Tawadros et al. (2006) in assigning the Greater Caucasus to the Hun (probably Cordillera) Superterrane.

The early Paleozoic location of the Greater Caucasus before the Hunic breakaway is uncertain. Tawadros et al. (2006) positioned it along the African-Arabian margin of Gondwana, but without constraining data. In the mid-Paleozoic, it was located near the easternmost extremity of the Hun Cordillera terranes with westward strike-slip dislocation along the northern Paleo-Tethys Shear Zone in the Carboniferous - Middle Triassic, and eastward dislocation in the Late Triassic - Early Jurassic (not depicted in figures in this paper). Such a late Paleozoic to Mesozoic shear zone may have stretched along the southern margin of Laurussia and connected with an intra-Pangean shear zone (Arthaud and Matte, 1977; Swanson, 1982; Rapalini and Vizán, 1993; Lawver et al., 2002; Stampfli and Borel, 2002; Bykadorov et al., 2003; Vai, 2003; Garfunkel, 2004; Natal'in and Sengör, 2005; Ruban and Yoshioka, 2005; Tawadros et al., 2006).

Stampfli and Borel (2002) positioned Kazakhstan (or parts of it) along the easternmost part of the Hun Superterrane suggesting proximity to the Greater Caucasus in the Devonian. Available paleontological data does not support this suggestion. The trilobite species *Paciphacops* occurs in the upper Silurian to Lower Devonian strata and its distribution encompasses the circum-Pacific (Merriam, 1973; Wright and Haas, 1990; Ramsköld and Werdelin, 1991; Edgecombe and Ramsköld, 1994). Its presence in Kazakhstan (Maksimova, 1968) and absence in Europe suggests the former was located on the margin of the Panthalassic Ocean, i.e. too far to be Hunic. This is also confirmed with other paleontological data (Blodgett et al., 1990; Campbell, 1977; Chlupác, 1975; Kobayashi and Hamada, 1977; Maksimova, 1972; Ormiston, 1972; Perry and Chatterton, 1976; Pedder and Oliver, 1990; Pedder and Murphy, 2004).

The Lesser Caucasus (Transcaucaus) terrane is presently located south of the Greater Caucasus, and north of Turkey and Iran (Figures 1 and 2). Interpretations based chiefly on paleomagnetic and paleontological data (Lordkipanidze et al., 1984; Gamkrelidze, 1986), indicate that it was apparently a separate terrane. It appears to have drifted northwards together with Cimmeria ("Iran-Afghan" microcontinent of Gamkrelidze). In the absence of conflicting evidence, we assign the Lesser Caucasus to Cimmeria. We also conclude that the paleopositions of the Caucasus along the margin of Gondwana or within the two superterranes remain unconstrained.

East Turkey, Northwest Iran and Alborz Terranes

The Eastern Turkey, Northwest Iran and Alborz regions are inconsistently interpreted in published reconstructions. Sengör (1990) interpreted Eastern Turkey as a Neo-Tethyan accretionary prism. Northwest Iran is considered Cimmerian and similarly depicted by several authors (e.g. Sengör, 1990; Sharland et al., 2001), but is sometimes referred to as the Alborz terrane by others (Stampfli et al., 2001; Torsvik and Cocks, 2004). In this review we consider Northwest Iran and Alborz as separate terranes (Figures 1 and 2).

Based on paleobiogeographic studies, Kolvoda (2002) suggested that the Alborz terrane was a part of the late Paleozoic Laurussia Supercontinent. Angiolini and Stephenson (in press), based on a re-examination of early Permian (Asselian-lower Sakmarian) brachiopods of the lower Permian Dorud Formation in the Alborz Mountains and a new study of palynomorphs from the same formation, also concluded that there is little affinity with Gondwana and the peri-Gondwanan region. Brachiopod fauna shows affinities with those of Baltica (Urals and of the Russian Platform), and to a lesser extent to the Trogkofel Limestone (Carnic Alps) in the west. The palynomorph assemblage is completely different from those recorded from the Asselian-Sakmarian *Granulatisporites confluens* Biozone, which is ubiquitous in the Gondwana region. L. Angiolini (2007, written communication) and coworkers, based on their studies and published data, concluded that the Alborz, Northwest and Central Iran remained adjacent to one another throughout most of the Paleozoic. This is reflected by the continuity and common evolution of their Paleozoic sedimentary rocks, and uniform distribution of biota. They attribute the similarity of the fossil record to the Urals to surface currents and the low latitudinal position of the Iranian terranes.

In summary, Eastern Turkey may not have been a Paleozoic terrane. The Alborz, Northwest and Central Iran terranes were apparently adjacent to one another. Their paleobiogeographic signature suggests a Laurussian affinity, but in the absence of more definitive data we follow most authors and assign them to the Cimmerian Superterrane.
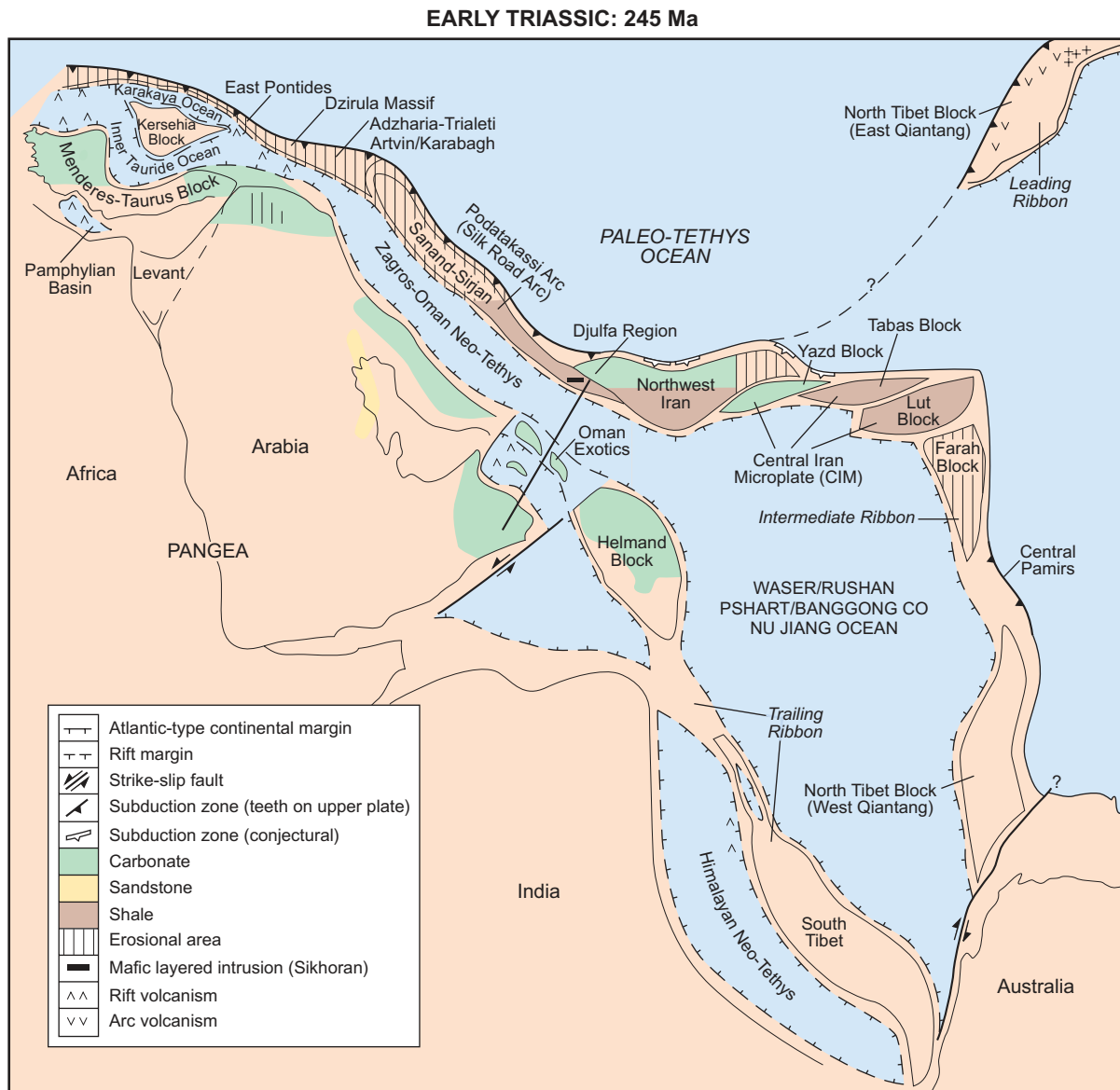
EARLY TRIASSIC: 245 Ma

Figure 11: Plate-tectonic reconstruction of the Early Triassic (modified after Sengör, 1990). Sengör interpreted the breakaway of the Cimmeria Superterrane to consist of three ribbons that detached at different times from Pangea. L. Angiolini (2007, written communication) and coworkers believe that this model is probably valid although it is very difficult to prove in detail. For example, their data suggests that the Helmand terrane may have been attached to the middle ribbon. Sengör interpreted the embryonic Neo-Tethys Ocean to consist of several seaways: Inner Taurides, Zagros-Oman, an unnamed sea south of Oman, Himalayan and Waser/Rushan-Nu Jiang. A subduction-arc complex is interpreted along the Paleo-Tethyan margin adjacent to the Sanandaj-Sirjan terrane and possibly extending further to the southeast and west. The initiation of subduction in mid-Carboniferous times may have caused the epeirogenic swells and compressional faulting in the Arabian Plate.

Sanandaj-Sirjan Terrane

The Sanandaj-Sirjan terrane (Figures 1, 2, 4 to 11) was attached to the Zagros Mountains (and the Arabian Plate) until it broke off as part of Cimmeria in the mid-Permian - Triassic (Berberian and King, 1981; Sengör, 1990; Grabowski and Norton, 1995; Stampfli et al., 2001; Sharland et al., 2001; Scotese, 2004). Most authors show the Paleozoic position of Sanandaj-Sirjan adjacent to the Zagros Suture, effectively implying that today it occupies the same approximate position as 250 million years ago.

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This seems remarkable as it was involved in the opening and closing of the Neo-Tethys Ocean. During the opening it may have subducted the Paleo-Tethys (Sengör, 1990), and during its closing, the Neo-Tethys (Ghasemi and Talbot, 2005).

Central Iran

Sengör (1990) divided the Central Iran microplate into the Lut, Tabas and Yazd blocks (Figure 11). Other authors consider Central Iran and Lut as synonyms (Stampfli and Borel, 2002; von Raumer et al., 2002, 2003; Torsvik and Cocks, 2004; Scotese, 2004; Golonka, 2004); or two neighboring terranes: Central Iran and Lut, or Yazd and Lut (e.g. Sharland et al., 2001; Stampfli et al., 2001). We adopt Sengör's Central Iran terrane and follow others by considering it as Cimmerian.

Zagros Mountains and Makran Region

The Zagros Mountains region in southwest Iran forms a part of the Miocene-Pliocene collision zone between the Arabian and Eurasian plates (Figure 1). This region was a part of the Arabian Plate from the late Neoproterozoic to the present-day (Berberian and King, 1981; Sepehr and Cosgrove, 2004). During the Permian-Triassic (Figures 10 and 11), the opening of the Neo-Tethys Ocean along the Zagros Suture Zone was accompanied by normal faulting and horsts and graben systems (Sepehr and Cosgrove, 2004).

South of the Zagros Mountains, the Makran region in Iran and Pakistan (Figure 1) consists of the Inner Makran ophiolites and the Cenozoic Makran and Saravan accretionary prisms (McCall, 1997, 2002, 2003). This region is associated with the NE-directed subduction of the Gulf of Oman oceanic crust (a remnant of the Neo-Tethys Ocean) beneath Iran. The Makran core may have amalgamated with Central Iran and Sanandaj-Sirjan during the Triassic (McCall, 2003). Therefore, Makran may have formed a part of Mesozoic Cimmeria.

Helmand and Farah Terranes

Afghanistan, western Pakistan and southeast Turkmenistan are cored by the southern Helmand and northern Farah terranes and considered Cimmerian (Figures 1 and 2; Sengör, 1990; Sharland et al., 2001; Stampfli et al., 2001; Golonka, 2004). Scotese (2004) adopted Sengör's (1990) model showing Helmand and Farah formed parts of two Permian-Triassic ribbons (Figure 11). Together with Karakoram in north Pakistan, the Farah and Helmand terranes are considered Cimmerian.

CONCLUSIONS

Recent publications that interpreted the Paleozoic tectonic units of the Middle East and their paleopositions were reviewed in the global context of supercontinents and exhumed vast oceans, to individual terranes. Adjoining the Arabian and Levant plates, ten Paleozoic Middle East terranes were apparently involved in the evolution of the Gondwana and Pangea margins and the Hun and Cimmeria superterranes. The Cimmerian terranes that broke off from Gondwana in mid-Permian - Triassic appear to have been: (1 and 2) Turkey's northern Pontides and southern Taurides; (3 to 6) Alborz, Central Iran (Lut, Tabas and Yazd), Sanandaj-Sirjan and Northwest Iran; (7 and 8) Helmand and Farah of Afghanistan, western Pakistan and southeast Turkmenistan; and (9) the Lesser Caucasus. The Greater Caucasus may have been Hunic.

The Caledonian and Hercynian orogenies occured far away from Arabia. Correlation between these two orogenies and deformations in Arabia can be misleading. They imply that far-field stresses were transmitted many thousands of kilometers from the orogenic fronts to Arabia's crust. The terms Caledonian and Hercynian should not be applied to the tectonic evolution of Arabia. Instead two significant and more proximal tectonic events were identified as possible near-field sources of regional deformation. The mid-Silurian breakaway of the Hun Superterrane is identified as a candidate that may be related to the mid-Silurian to Middle Devonian (middle Paleozoic) uplift in North Arabia and possibly Oman. The initiation of subduction, which could have preceeded the mid-Permian - Triassic breakaway of Cimmeria, is considered a possible force for the regional mid-Carboniferous faulting and epeirogenic deformation in Arabia.

Middle East plate-tectonic models require much more data and investigations if they are to be firmly constrained. The first step is to adopt common boundaries and names for the terranes, not only for the Middle East, but also of those in Asia and Europe (Figures 1 and 2). The second step requires constructing a regional tectono-stratigraphic framework that crosses from the interior of the Arabian Plate and its outer margins (Oman, Zagros, North Iraq, Syria and Southeast Turkey) to the ten and possibly more Middle East terranes. The framework requires correlating stratigraphic rock units that are much better constrained by age (biostratigraphy), paleontology and tectonics. Additionally, paleomagnetic and age data, together with the descriptions and interpretations of volcanic rocks could better clarify many aspects of the tectonic events.

ACKNOWLEDGEMENTS

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