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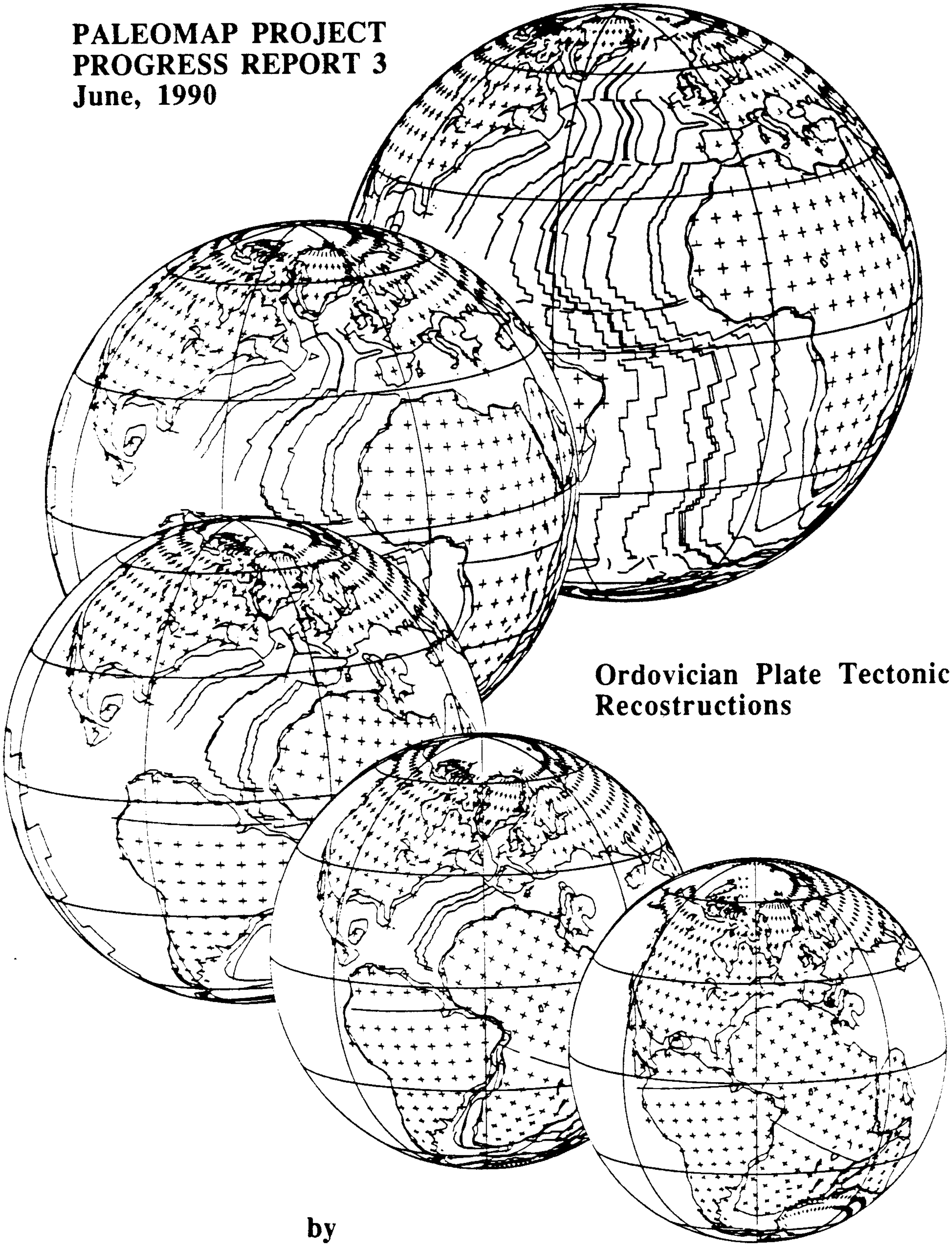

Ordovician Plate Tectonic Recostructions

by

W. S. McKerrow and C. R. Scotese

ORDOVICIAN PLATE TECTONIC RECONSTRUCTIONS

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Abstract

Plate tectonic reconstructions are presented for the Tremadoc, Arenig, Llandeilo-Caradoc, and Ashgill. During the Ordovician, the major continents were Laurentia (North America), Baltica (Northern Europe), Siberia/Kazakhstan, and Gondwana, which included China and Southeast Asia. These continents were separated by three large oceans: Iapetus, Paleotethys, and Panthalassa. Lower Paleozoic plutonism, island arc activity, metamorphism, and in some cases ophiolites, in eastern Australia, East Antarctica, western South America and North America, Arctic Canada, Mongolia, Kazakhstan, and north-central China, suggest that during the Ordovician, continents were encircled by a Panthalassic subduction zone. During the late Cambrian or Early Ordovician, Avalonia rifted away from the northern margin of Gondwana, widening the Paleotethys and narrowing the Iapetus. The collision of the Bronson Hill-Tetagouche-Lush's Bight island arc along the eastern margin of Laurentia during the Middle Ordovician resulted in the Taconic Orogeny and the initiation of northwesterly directed subduction beneath Laurentia, which ultimately lead to the closure of the Iapetus Ocean in the middle Paleozoic. In most respects, the number, size, and rate at which the plates moved during the Ordovician were comparable to present-day plate geometry and motion.

INTRODUCTION

The Ordovician is the oldest time period for which accurate plate tectonic reconstructions can be made. Plate tectonic reconstructions for the Cambrian and late Precambrian (Bond et al., 1984; Piper, 1983, 1987; Parrish et al., 1986; Kirschvink, 1990) remain speculative due to the absence of a global biostratigraphic standard, the paucity of reliable paleomagnetic results (Van der Voo et al., 1984) and the uncertainty concerning the absolute age of the Cambrian/Precambrian boundary (Cowie and Brasier, 1989; Moczydlowska and Vidal, 1988). In this paper we present plate tectonic reconstructions for the Tremadoc, Arenig, Llandeilo-Caradoc, and Ashgill epochs.

Ordovician paleomagnetic results from North America (Van der Voo, 1988; Kent and Van der Voo, 1990), Europe (Torsvik et al., 1990), Siberia (Khramov and Rodionov, 1980; Khramov et al., 1981), South China (Lin et al., 1985a, b) and Gondwana (Bachtadse and Briden, 1990) provide the framework for the reconstructions. These paleomagnetic constraints have been supplemented with information from paleoclimatology (Scotese and Barrett, 1990), biogeography (McKerrow and Scotese, 1990), and plate kinematics. We estimate that there is a +15° uncertainty in the latitudinal positions of the major continents, and a +30° uncertainty in their relative longitudinal positions.

The poles of rotation used to reassemble the supercontinents of Gondwana and Laurentia are given in Table 1. The total finite rotation poles used to orient the major continental blocks relative to the geographic pole are listed in Table 2.

In addition to illustrating the positions of the ocean basins and continents (Fig. 1), we have attempted to plot the location of Ordovician subduction zones and regions of inferred plate divergence (arrows, Figs. 2-5). During the Ordovician there were four major convergent boundaries. Two subduction zones lay on either side of the Iapetus Ocean. One of these subduction zones ran along the northwest coast of Avalonia and a slightly younger, westward-dipping subduction zone was located along the eastern margin of Laurentia. A third major subduction zone stretched across the northern margin of Gondwana, and a fourth, the Panthalassic subduction zone, encircled Gondwana, Siberia, and the northern and western coasts of Laurentia (Fig. 1).

The areas of the plate divergence shown in Figures 2-5 are speculative. Except for ophiolitic remnants, no direct evidence exists concerning the location or orientation of ancient spreading centres, or the rates of sea floor spreading. The spreading directions shown in these figures have been drawn to account for the relative motion of the continents and to provide oceanic crust for the Ordovician trenches.

It should be noted that there have been several previous attempts to reconstruct Ordovician plate boundaries (Keppie, 1977; Zonenshain and Gorodnitsky, 1977; Kanasewich et al., 1978; Seslavinsky, 1984; Zonenshain et al., 1985, 1987). The maps presented here, although similar to these earlier attempts, are more detailed and are based on a new synthesis of paleomagnetic, paleoclimatic, and biogeographic data.

ORDOVICIAN OCEANS AND CONTINENTS

The Ordovician world, like the present-day, was made up of groups of continents separated by large ocean basins. The Iapetus Ocean separated Laurentia/Siberia from Baltica (Fig. 1). Baltica, in turn, was separated from Gondwana by the Paleotethys, which extended eastward along the northern margin of Gondwana (Fig. 1). The Panthalassic Ocean, like the modern Pacific, was bounded by subduction zones and encircled the entire ensemble of continents (Fig. 1).

Iapetus Ocean

The Iapetus Ocean probably originated when the southern margin of Baltica rifted away from the eastern margin of Laurentia during the latest Precambrian (600-550 Ma, Williams and Hiscott, 1987; Bond et al., 1984). It widened throughout the Cambrian, and was widest during Late Cambrian/Early Ordovician time. In the Early Ordovician, a transform boundary in the Iapetus Ocean converted to a southeast-dipping subduction zone bounding a northwest-facing arc (McKerrow et al., 1990), and the Iapetus Ocean began to narrow. Apart from pandemic pelagic faunas and deep water benthos, the marine faunas of the continents bordering Iapetus were distinct during the Early and Middle Ordovician, suggesting that Laurentia, Baltica and the northern margin of Gondwana were separated by oceans at least 1000 km wide (Cocks and Fortey, 1982) (Fig. 2).

In Figures 2 and 3, an island arc is shown adjacent to the southern margin of Laurentia. The Lower Ordovician benthic faunas of these island arcs (Bronson Hill, Tetagouche, and Lush's Bight) have been considered sufficiently distinct from those of Laurentia, Baltica, and Gondwana to justify a separate "Celtic Province" (Neuman, 1984). However, recent descriptions of similar fossils from both Laurentia and Avalonia (McKerrow and Cocks, 1986) would suggest that environmental factors, rather than geographic isolation, were responsible for these peculiar faunas. We believe that parts of this arc had already collided with the Grampian Highlands of Scotland prior to the Arenig, and that parts of the island arc could not have been far removed from northern Newfoundland, as collision took place there in Llanvirn time. Geographic isolation of these arc faunas from Laurentia would thus have been unlikely. The collision of these island arcs with the eastern margin of Laurentia resulted in the Taconic Orogeny.

During the Early Ordovician, the ocean floor was subducted to the southeast, beneath the Avalonian margin of Iapetus (northern Gondwana). In Figures 3 and 4, the Avalonian island arc, comprising England, Wales, southeastern Ireland, the Avalon Peninsula of eastern Newfoundland, parts of coastal New Brunswick, Nova Scotia, and coastal New England, is shown rifting from northwestern Gondwana. Calc-alkaline arc rocks appear in England, Wales, and Ireland in the Tremadoc (Kokelaar et al., 1984). This subduction zone appears to have become inactive after the Llandeilo-Caradoc (Figs. 4, 5), and a new subduction zone was initiated along the northwestern margin of Iapetus following the collision of the Bronson Hill-Tetagouche-Lush's Bight (BTL) arc with the eastern margin of Laurentia (McKerrow et al., 1990).

By the Middle Ordovician, the benthic faunas of eastern Avalonia started to lose their affinities with Gondwana and began to show more similarities to faunas from Baltica. The faunas of Avalonia and Baltica became identical in the late Caradoc (Fortey and Cocks, 1986) indicating that the Tornquist Sea between Avalonia and Baltica (Fig. 1) was narrow enough for cratonic benthos to cross easily. This connection occurred significantly earlier than the late Ashgill connection of benthic faunas across Iapetus between Baltica and Laurentia (McKerrow and Cocks, 1986; Cocks and Fortey, 1982).

Although we consider Avalonia to be composed of terranes from both sides of the Atlantic, the location of the western portions of Avalonia (Nova Scotia, and the eastern regions of Newfoundland, New Brunswick, and New England) is more uncertain. In southern Nova Scotia, the very thick clastic sequence of the Meguma Group extends upward to include Lower Ordovician sediments. No comparable sequence is known elsewhere in Avalonia, and it may be that the Meguma Terrane was originally separated from the rest of western Avalonia. Tillites have been described from the Roxbury Conglomerate of the Boston Bay Group, but their age is unknown. Tillites have also been described from Nova Scotia (Schenk, 1972). If Ashgill tillites were present in western Avalonia, western Avalonia would have been at a higher latitude than the eastern part of Avalonia. The location of the Avalon-Acadia terranes shown in Figures 2-4 is consistent with paleomagnetic results that place these terranes at temperate paleolatitudes during the early Paleozoic (Johnson et al., 1988).

Subduction beneath eastern Laurentia throughout the remainder of the Ordovician resulted in the narrowing of the Iapetus, and lead to the eventual collision of Baltica with Laurentia during the mid-Silurian (McKerrow et al., 1990). The last remnants of Iapetus oceanic crust were consumed when Avalonia, which rifted away from Gondwana during the Early Ordovician, collided with Laurentia during the Late Silurian and Early Devonian (Caledonian/Acadian orogenies).

Paleotethys Ocean

Sengor (1984, 1987) recognized that the Tethys Ocean of Seuss (1893) was not a single ocean basin, but rather represented several generations of rifting, subduction, and continental collision. We use the term "Paleotethys" (Proto-Tethys of Ziegler, 1988) to describe the Paleozoic ocean basin separating the northern margin of Gondwana from the southern margin of Baltica and the southwestern margin of Siberia/Kazakhstan (Fig. 1).

Southern Margin of Paleotethys

Like the modern western Pacific, the southern margin of Paleotethys was a major convergent plate boundary and the site of widespread back-arc basin formation (see Fig. 1, Cimmerian-Cathaysian subduction zone, cc). During the Paleozoic, numerous continental fragments rifted away from the northern margin of Gondwana and were eventually welded together to form much of south-central Europe (Ziegler, 1988), China, and Southeast Asia (Sengor, 1989; Nie et al., 1990).

Although the original position of these continental fragments is not well known, a variety of biogeographic, paleoclimatic, and paleomagnetic constraints can be used to infer their relative positions. Proceeding from southwest to northeast along the northern margin of Gondwana (Fig. 1), the major continental fragments are: south-central Europe, Turkey, Iran, Afghanistan, South China (Yangtze block) and Tarim, Indochina, Qiangtang, Lhasa, Greater India, Burma-Malaya, and North China (Sino-Korean platform).

South-Central Europe, Turkey, Iran and Afghanistan

South-central Europe includes Iberia, France (Armorica), parts of West Germany, and the Bohemian massif. Paleomagnetic data from western France (Perroud and Van der Voo, 1985) and Spain (Perroud, 1983; Perroud et al., 1984), indicate that these areas were at high southern latitudes during the Ordovician (Torsvik et al., 1990), which is consistent with a position adjacent to the North African margin of Gondwana. Faunal evidence (Cocks and Fortey, 1982) supports the conclusion that these parts of Gondwana, together with Avalonia, bordered the southern margin of the Paleotethys Ocean. Deeper water facies, marginal to Gondwana, are present in the Ardennes of northern France, and in Bohemia, indicating that these parts of Europe also lay along the margin of Gondwana (Cocks and Fortey, 1982). The lower Paleozoic sequences of Morocco, Spain, France, and Bohemia are dominated by clastic sediments; there are no deposits of warm-water limestones from the Middle Cambrian through to the mid-Devonian, suggesting that these regions of Gondwana were located at high latitudes near the South Pole.

Both Turkey and Iran are composites of several continental fragments. Turkey, north of a suture that runs parallel to the Anatolian fault (intra-Pontide suture), is considered to be a rifted fragment of south-central Europe (Sengor and Yilmaz, 1981), whereas the regions south of the fault have faunas with mixed Gondwanan and Asian affinites. The location of southern Turkey during the Ordovician is not well constrained; we follow Dewey et al. (1973) and Geley (1988), who suggested that Turkey rifted from the northern coast of Egypt in the Late Triassic/Jurassic.

The major terranes that constitute Iran are the Alborz block, Lut block, and the Sanandaj-Sirjan zone. the Helmand (Sistan) block of Afghanistan appears to be closely associated with the Lut block of Iran. The Early Cambrian (or latest Precambrian) salt deposits of central Iran were probably once adjacent to similar salt deposits now found in the Persian Gulf, Oman, and Pakistan. In the reconstruction presented here, we place the Lut block of Iran and the Helmand block of Afghanistan in the gap between India and Arabia (Fig. 1). This position is consistent with Lower Devonian paleomagnetic data that suggests a location adjacent to India (Wensink, 1983). Mid-Devonian through Permian volcanic rocks in the Sanandaj-Sirjan zone (Berberian and King, 1981) indicate that this linear zone was either an island arc or Andean-style margin along the northern edge of Gondwana.

South China and Tarim

The position of South China and Tarim differs from the recently published reconstructions of Scotese and McKerrow (1990), and is similar to the reconstruction proposed by Burrett et al. (1990). South China is rotated 180°, so that its present-day eastern margin faces northwest. Biogeographic affinities suggest that South China was located near northwestern India and Pakistan during the Early Cambrian (Chang, 1981), although connections with North China and Australia are also maintained throughout the early Paleozoic (Burrett et al., 1990).

The occurrence of the Lower Ordovician trilobite, *Neseuretus* (Fortey and Morris, 1982), in South China indicates that there were biogeographic connections between South China, Arabia and south-central Europe. *Neseuretus* has been interpreted as a cold, shallow water fauna and its appearance in South China may reflect its southward movement into temperate latitudes during the Early Ordovician (Fig. 2). The orientation of South China shown in Figures 2-5 is consistent with Cambrian (Lin et al., 1985a, b), Silurian (Opdyke et al., 1987), and Devonian (Fang et al., 1990) paleomagnetic data.

The paleoposition of Tarim is still unknown. Late Precambrian and lower Paleozoic lithofacies, including lower Sinian tillites (Wang et al., 1985), archaeocyathids (Zhuravlev, 1986), and Lower Cambrian phosphorites (Notholt and Sheldon, 1986) indicate a closer association with South China than with North China. For these reasons we believe that Tarim was adjacent to South China and Indochina, but outboard of the Qiangtang and Burma-Malaya continental blocks (Fig. 1).

Indochina, Qiangtang, Lhasa and Greater India

Very little is known about Indochina during the Ordovician, however, metamorphic rocks of early Paleozoic age (Hurley and Fairbairn, 1972) indicate that it may have formed part of the northern Gondwana subduction zone. Inboard of Indochina are Qiangtang/Lhasa, and Greater India. Qiangtang has been subdivided into eastern and western terranes (Nie et al., 1990). Western Qiangtang has strong Gondwanan affinites, including upper Paleozoic tillites and faunas (*Eurydesma*). Between Qiangtang and Greater India lies the Lhasa block, which, like Qiangtang, has Lower Permian tillites and a stratigraphy similar to northern India (Xizang Scientific Expedition, 1987). The Qiangtang and Lhasa blocks, together with Turkey, Iran, Afghanistan, and Burma-Malaya, formed the Cimmerian continent that rifted away from the northern margin of Gondwana during the late Paleozoic (Sengor, 1989; Nie et al., 1990). Cimmeria collided with Asia during the early Mesozoic, closing the Paleotethys Ocean (Sengor, 1984).

Between Qiangtang/Lhasa, the Indian Shield, and western Australia lies "Greater India". This vast region of continental crust is the northern extension of the Indian Shield. During the mid-Tertiary, Greater India was apparently subducted beneath Asia, forming part of the Tibetan plateau (Powell and Conaghan, 1973; Veevers et al., 1975).

Burma-Malaya and North China

The Burma-Malaya block, or Sibumasu, or Shan-Thai, as it is sometimes called, is shown adjacent to the northwestern coast of Australia. Faunal ties between Burma-Malaya and northwestern Australia were strong during Late Cambrian and Ordovician time, as shown by the close faunal affinities of trilobites, molluscs, stromatoporoids, brachiopods, and conodonts (Burrett et al., 1990). The position of Burma-Malaya, shown in Figure 1, is consistent with the orientation predicted by Permian paleomagnetic data (McElhinny, 1981; Fang and Van der Voo, 1990). The occurrence of probable upper Paleozoic glacial diamictites (Phuket Group; Metcalfe, 1983) indicates that the Burma-Malaya block was still within the range of Permo-Carboniferous ice-rafted debris. An earlier phase of rifting between Burma-Malaya and Australia resulted in the eruption of the Antrim flood basalts, which once covered much of northwestern Australia (Veevers, 1984).

The North China block is shown adjacent to northernmost Australia. It has been rotated 180° so that the Qilian Shan subduction zone is aligned with the Tasman-Trans-Antarctic subduction zone (Fig. 1). During the Early and Middle Ordovician, North China had strong biogeographic ties with Australia and Burma-Malaya (Burrett et al., 1990). Faunal similarities with Laurentia during the late Cambrian may be because both continents occupied equatorial positions and faunas were able to cross Panthalassa via the western equatorial gyre.

Northern Margin of Paleotethys

Avalonia, Baltica, and Kazakhstan bordered the northern margin of Paleotethys during the Ordovician (Fig. 1). The southern extent of Baltica is poorly known and it is likely that Baltica was a larger continent and extended farther south during the Ordovician. The Donetz Graben, located in the southeastern corner of Baltica, is the failed arm of a Devonian rift (Khain, 1985). At present we do not know which continent rifted away from Baltica, or how large this continent may have been.

Previous reconstructions (e.g., Scotese et al., 1979; Scotese, 1984), have treated Kazakhstan as a separate and independently moving paleocontinent, but we now consider Kazakhstan to be an amalgamation of volcanic arcs and far-travelled terranes that extended eastward from the Siberian plate. We propose that the relationship of Kazakhstan to Siberia was similar to the present-day relationship of southeast Asia to mainland China. The complex and often mixed aspect of the faunas of Kazakhstan may be explained, in part, by the fact that Kazakhstan is a collage of exotic and far-travelled terranes.

Panthalassic Ocean

Panthalassa, the "universal sea", was the name given by the ancient Greeks to describe the vast oceanic expanse surrounding the known world. In Wegener's (1929) scheme, Panthalassa became the primordial ocean, just as Pangea was the primordial continent. Although not as vast as its Upper Paleozoic counterpart, the Ordovician Panthalassa was as wide at the equator as the present-day Pacific Ocean and included a hemispherical cap that covered the northern half of the globe (Figs. 2-5).

We propose that, like the modern Pacific Ocean basin, the Panthalassic Ocean was ringed by subduction zones (Scotese, 1987). Proceeding clockwise around Panthalassa from a starting point in eastern Australia, the components of the circum-Panthalassic subduction zone were: the Tasman-Trans-Antarctic subduction zone (tt), the Puna-Arequipa-Perija subduction zone bordering western South America (pap), the Chiapas-Klamath-Alexander subduction zone along western Laurentia (cka), the North Slope-Ellesmere subduction zone across the northern part of Laurentia (ne), the Mongolian-Kazakhstan subduction zone (mk), and the Qinling-Qilian Shan subduction zone (qq), which linked up with the northern part of the Tasman-Trans-Antarctic subduction zone to complete the circuit (Fig. 1). The best documented portions of these Ordovician convergent boundaries are the Tasman-Trans-Antarctic subduction zone (Schreibner, 1987; Veevers, 1984) and the Mongolian subduction zone (Zonenshain et al., 1971).

Much of the circum-Panthalassic subduction zone appears to have been active in the late Precambrian and although the record is incomplete, subduction along most of these margins appears to have continued through the Paleozoic and into the Mesozoic and Cenozoic. We suggest that the subduction zones ringing the present-day Pacific Ocean are the direct descendants of these ancient Panthalassic subduction zones.

Tasman-Trans-Antarctic Subduction Zone

The Tasman orogenic belt of eastern Australia can be divided into three regional provinces: the Kanmantoo fold belt, the Lachlan fold belt, and the New England fold belt. The westernmost belt, the Kanmantoo Orogen was tectonically active from the late Precambrian until the Early Ordovician (Veevers, 1984). The central belt, the Lachlan fold belt is the most extensive and was the site of plate convergence from the Cambrian to the Middle Carboniferous. The early Paleozoic history of the New England fold belt is uncertain, but the belt was active during the Silurian and continued to be active until the mid-Cretaceous (Veevers, 1984).

Upper Precambrian igneous and metamorphic rocks and lower Paleozoic granitic plutons of the Trans-Antarctic mountains represent the continuation of the Tasman fold belt into Antarctica (Kleinschmidt and Tessensohn, 1987). Three orogenic episodes have been recognized (Elliot, 1975): the late Precambrian Beardmore Orogeny, the Cambro-Ordovician Ross Orogeny, and a middle Paleozoic orogenic episode (Elliot, 1975). Devonian quartz diorites from Marie Byrdland (Halpern, 1968) indicate that the Trans-Antarctic subduction zone moved outward from the East Antarctic craton during the middle Paleozoic, possibly as a result of progressive continental accretion or the collision of exotic terranes. Recently, radiometrically dated metamorphic rocks of Paleozoic age from the West Antarctic peninsula indicate that this area may also have been the site of Paleozoic subduction.

Puna-Arequipa-Perija Subduction Zone

During the Ordovician, the Panthalassic subduction zone crossed the Falkland Plateau, traversed northwestern Argentina and exited near Concepcion on the Chilean coast. The Puna magmatic arc of northwestern Argentina is considered to be the equivalent of the Ross orogenic belt (Aceñolaza and Miller, 1982). No Precambrian rocks have been identified outboard of this margin, and the suture with allochthonous Patagonian terranes is marked by an Ordovician and Silurian flysch basin that crops out in the coastal ranges of central Chile and the pre-Cordillera of Argentina (Frutos and Tobar, 1975).

Little evidence now exists for the continuation of the Panthalassic subduction zone along the western coast of South America. As noted above, the subduction zone appears to strike out to sea in the vicinity of Concepcion, Chile. The only other remnants of Panthalassic subduction are the Devonian metamorphic and plutonic rocks of the Arequipa Massif of southern Peru (Megard, 1987), and the lower Paleozoic metamorphic basement rocks of the Merida and Perija Andes in Colombia and Venezuela. In Colombia, slightly metamorphosed fossiliferous strata of Ordovician age are associated with gneiss, quartzites, phyllites, and amphiobolites, and are overlain by marine clastics of Early Devonian age (Floresta Formation; Burgl, 1973). In Venezuela a similar lower Paleozoic igneous and metamorphic basement is overlain by Devonian fossiliferous limestones (Zambrano et al., 1972).

The missing segment of the Panthalassic subduction zone may have been removed by rifting or by ''tectonic erosion''. Ziegler et al. (1981) suggested that much of west-central South America may have been tectonically eroded by subduction during the Mesozoic and Cenozoic. Thick accumulations of Devonian sandstone and siltstone in southern Peru and Bolivia imply that the Arequipa Massif, the source of these sediments, may originally have been more extensive (Isaacson and Sablock, 1990).

Chiapas-Klamath-Alexander Subduction Zone

The continuation of the Panthalassic subduction zone along the western margin of Laurentia is recorded in the lower Paleozoic metamorphic terranes of northwestern Honduras, southwestern Mexico, as well as in the lower Paleozoic metamorphic, volcanic, and plutonic complexes of the Klamath mountains and Alexander Terrane of southwestern Alaska. Upper Precambrian and lower Paleozoic metamorphics and metavolcanics, including a high pressure, low temperature phase that has been dated as Early Ordovician (de Csema, 1989), have been reported from Chiapas and the Acatlan Terrane (Sierra Madre del Sur) of southwestern Mexico (Ortega-Gutierrez, 1982). Subduction in this area continued through the middle and late Paleozoic (de Csema, 1989).

The lower Paleozoic volcanic arc of the Klamath mountains in northern California represents the northward continuation of the Panthalassic subduction zone. Ordovician tonalitic and pegmatitic trondjemites from the Trinity ophiolite (Wallin et al., 1988), and associated Upper Ordovician calc-alkaline basalts with strong island arc affinites (Lovers Leap Butte volcanics, Brouxel et al., 1988) indicate that subduction along the western margin of Laurentia extended back into the early Paleozoic. This interpretation assumes that the Klamath volcanic arc is not a far-travelled terrane (Schweikert and Snyder, 1981), but rather originated in a back-arc setting (Burchfiel and Davis, 1972, 1975; Gray, 1986). Although arguments have been made for both interpretations, paleomagnetic data (Fagin and Gose, 1983) and mixed Tethyan and North American biogeographic affinities (Miller and Wright, 1987) suggest proximity to Laurentia. Although adjacent to North America, the Klamath volcanic arc was far offshore and did not influence foreland-platform sedimentation.

The volcanic arc that fringed Laurentia during the Ordovician continued northward in the Alexander terrane of British Columbia and southeastern Alaska. In these areas, Cambrian and Middle Ordovician metamorphic rocks, together with Ordovician and Silurian turbidites, calc-alkaline intrusives, and minor volcanics (Descon Formation) form the basis of the arc (Gehrels and Saleeby, 1987a). As in the case of the Klamath volcanic arc, it has been proposed that the Alexander Terrane is allochthonous and possibly far-travelled (Gehrels and Saleeby, 1987b). We find no compelling evidence for an exotic origin of the arc and agree with earlier authors (Churkin, 1974) who place the Alexander arc near the Laurentian margin.

North Slope-Ellesmere Subduction Zone

In the reconstruction of Laurentia presented here, the North Slope block of Alaska has been refitted against the Canadian Arctic Islands by a rotation about a pivot-point near the Mackenzie Delta (for a review see Lawver and Scotese, 1990). As illustrated in Figure 1, the Panthalassic subduction zone swung eastward across the North Slope, the eastern portion of the Canadian Arctic Islands (Ellesmere Island), and northern Greenland. The Precambrian(?) and lower Paleozoic metasedimentary and metavolcanic rocks of the Skajit allochthon of the Central Brooks Range (North Slope block) represent an island arc that fringed this subduction zone. Further evidence of island arc activity is seen in northwestern Ellesmere Island and Axel Heiberg Island where upper Precambrian through Silurian volcanics and flysch comprise the complexly deformed Pearya island arc (Trettin, 1989). Included in this sequence are a Lower Ordovician ophiolite (Thores suite) and amphibolite-grade metamorphic, which give Middle-Late Ordovician ages (452 Ma; Trettin, 1989). The deep water, lower Paleozoic sedimentary basin in northern Greenland represents a foredeep behind this volcanic arc.

Mongolian-Kazakhstan Subduction Zone

Numerous lower and middle Paleozoic calc-alkaline volcanics, metamorphics, and obducted ophiolites make the Mongolian-Kazakhstan subduction zone one of the best documented Paleozoic convergent plate boundaries (Zonenshain et al., 1971; Zonenshain, 1973). Built on pre-

Riphean metamorphic basement (>1100 Ma), the Mongolian-Kazakhstan island arc was active from the late Precambrian (Mossakovsky and Dergunov, 1985) to the Permian, when subduction was terminated by the collision of the Tarim and North China blocks (Nie et al., 1990).

The original geometry of the arcs and subduction zones was certainly more complex than shown in Figures 2-5. Multiple ophiolite sequences (Zonenshain, 1973) indicate a succession of back-arc basin formation and collapse. Also, as proposed by several authors (Zonenshain et al., 1985; Rowley et al., 1985; Nie et al., 1990), an eastern extension of the Mongolian arc (Amuria, Zonenshain et al., 1985) was separated from mainland Siberia by a small ocean basin that did not close until the Late Jurassic.

As discussed earlier, Kazakhstan is an agglomeration of island arcs and exotic terranes. Although part of a separate subduction system, we believe that the island arcs of Kazakhstan were closely linked to the Mongolian subduction zone. As in Siberia, subduction continued throughout the Paleozoic, terminating in the Permian with the closure of the Irtysch Seaway between Kazakhstan and Siberia, and the suturing of Tarim (Tian Shan suture) and Baltica (Uralian suture).

Qinling-Qilian Shan Subduction Zone

Our tour of the Panthalassic subduction zone is complete as we return to Gondwana and connect the Mongolian subduction zone with the Qinling-Qilian Shan subduction zone of North China. The Qinling suture is the boundary between North China and South China (Nie et al., 1990). It is presumed to have been the site of subduction during the Paleozoic and the locus of continental collision during the Late Triassic Indosinian Orogeny (Sengor, 1984). The Qilian Mountains, located between the Ordos Basin and the Tarim block, are the westward continuation of the Qinling mobile belt. This interior mountain range consists of a series of upper Precambrian-lower Paleozoic island arcs, which collided against an Andean-style margin (Yang et al., 1986). The lower Paleozoic section includes over 10,000 metres of deep water clastics, siliceous and carbonaceous rocks, and volcanics. The peak of magmatic activity occurred during the Ordovician, with abundant intermediate and intermediate-basic volcanics (Yang et al., 1986), which were metamorphosed to greenschist facies during the middle and late Paleozoic.

In its present-day location the Qinling-Qilian Shan subduction zone appears anomalous; however, in the reconstruction presented here (Fig. 1), it forms a plausible continuation of the Tasman subduction zone. In this reconstruction (after Burrett et al., 1990), North China is shown rotated 180° and placed against the northern margin of Australia. This aligns the Qilian Shan subduction zone with the New England fold belt of eastern Australia.

CONCLUSIONS

From the plate boundaries described in Figures 2-4, it can be inferred that there were six to eight major plates during the Ordovician that were roughly comparable in size to modern plates. The rates of plate motion, based on the trajectory of the continents, were also similar to modern rates of plate motion. Based on the scenario presented here, Laurentia was the fastest moving continent, travelling eastward at rates of 15 cm/y during the Early and Middle Ordovician. Rates in excess of 10 cm/y are indicative of plates that are connected to a large subducting slab, like the modern Pacific Plate (Forsyth and Uyeda, 1975) or the Indian Plate during the Late Cretaceous and Early Tertiary (Scotese et al., 1988). In the case of Laurentia, the southern and eastern portions of the plate were subducted beneath the Avalonian arc and the Bronson Hill-Tetagouche-Lush's Bight arc (Figs. 2, 3). After collision with the Bronson Hill-Tetagouche-Lush's Bight arc and the ensuing reversal of subduction polarity (Figs. 4, 5), Laurentia's rate of motion abruptly slowed. Throughout the Ordovician, Baltica and Siberia moved northward at the moderate rate of 6 to 8 cm/y, while Gondwana moved southward over the South Pole at a similar pace.

Although preliminary, the Ordovician plate tectonic reconstructions presented here can be used as a framework for a better understanding of the paleobiogeography, paleoclimatology, and paleoceanography of the Ordovician. Only through an interactive process of revision and refinement in the light of new geological, tectonic, paleontological, and paleomagnetic data will we be able to unveil the secrets of the early Paleozoic world. Although the clues are sparse and often subject to alternative interpretations, it should be remembered that the same plate tectonic driving forces that produced the Mesozoic and Cenozoic ocean basins were also in operation during the Paleozoic. In this regard, the pattern of Paleozoic plate evolution, once it is understood, should be characterized by the same simplicity and elegance that characterizes Mesozoic and Cenozoic plate evolution.

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FIGURE CAPTIONS

Figure 1. Key to geographic locations mentioned in text. Continental blocks: BR = Barentsia (Svalbard), ENG = England and Wales, NE = New England and Maritime Canada, YU = Yucatan, PD = Florida and Piedmont of southeastern U.S.A., SC = South-Central Europe, TR = Turkey, SC = South China, IR = Central Iran and Afghanistan (Helmand), IN = Indochina, QT = Qiangtang and Lhasa, GI = Greater India, BM = Burma-Malaya, NC = North China, NNZ = North New Zealand, SNZ = South New Zealand; Island arcs and subduction zones: cka = Chiapas-Klamath-Alexander arc, ne = North Slope Alaska arc, mk = Mongolian-Kazakhstan subduction complex, av = Avalonian arc, btl = Bronson Hill-Tetagouche-Lush's Bight arc (shown sutured to Laurentia), cc = Cimmerian-Cathaysian subduction complex, qq = Qinling-Qilian Shan Subduction zone, tt = Tasman-Trans-Antarctic subduction zone, pap = Puna-Arequipa-Perija subduction zone. The South Pole is indicated by the diamond symbol near Spain. (Middle-Late Ordovician reconstruction, Oblique Mollweide projection.)

Figure 2. Earliest Ordovician (Tremadoc) plate tectonic reconstruction. Bold lines = subduction zones, arrows indicate areas of probable plate divergence (seafloor spreading).

Figure 3. Early Ordovician (Arenig) plate tectonic reconstruction. Bold lines = subduction zones, arrows indicate areas of probable plate divergence (seafloor spreading).

Figure 4. Middle-Late Ordovician (Llandeilo-Caradoc) plate tectonic reconstruction. Bold lines = subduction zones, arrows indicate areas of probable plate divergence (seafloor spreading).

Figure 5. Late Ordovician (Ashgill) plate tectonic reconstruction. Bold lines = subduction zones, arrows indicate areas of probable plate divergence (seafloor spreading).

TABLE 1
Rotation poles used to assemble Gondwana and Laurentia

A. GONDWANA (ROTATIONS WITH RESPECT TO FIXED AFRICA)

Part 1. Central Gondwana

Continental Block	Latitude	Longitude	Angle
South America	45.5	-32.30	58.20
Madagascar	-1.7	-87.80	22.20
Arabia	-26.50	-158.50	7.60
India	-28.10	-136.70	66.50
Sri Lanka	-18.00	-128.60	90.50
Australia	-24.63	-62.64	55.92
East Antarctica	-9.68	-31.81	58.54

Part 2. Northwest Margin

Continental Block	Latitude	Longitude	Angle
Florida/Piedmont	62.2	-15.90	78.80
Yucatan	48.36	97.02	66.00
Iberia	-39.44	165.60	25.40
South-Central Europe	41.85	36.60	13.67
Apulia/Adria	43.78	47.30	14.62
W. Avalonia	61.68	-4.03	71.23
E. Avalonia	25.60	16.60	39.42
Turkey	-46.50	174.0	7.70

Part 3. Northeast Margin

South China	6.39	89.93	93.34
Qiangtang/Lhasa	-32.44	-145.90	49.66
Indochina	-12.18	93.92	62.85
Burma-Malaya	1.95	102.57	86.79
North China	15.06	131.53	112.1

Part 4. Southeast and Southwest Margin

N. New Zealand	4.83	-54.80	84.68
S. New Zealand	29.93	-58.89	103.9
Marie Byrdland	3.19	-33.40	61.47
W. Antarctic Pen.	-36.90	-19.92	81.40

B. LAURENTIA (ROTATIONS WITH RESPECT TO NORTH AMERICA FIXED)

Continental Block	Latitude	Longitude	Angle
Greenland	-50.07	26.29	7.74
Alaska N. Slope	-70.11	51.84	78.00
Mexico	-48.60	94.10	13.00
Baja California	-51.12	80.89	5.63
Arctic Islands	-50.07	26.29	7.74
Chortis/Honduras	-42.66	88.53	43.96
N. Scotland	-82.30	-25.90	33.50
Barentsia (Svalbard)	-81.45	110.7	50.10

TABLE 2

Rotation poles used to reconstruct major plates relative to geographic pole

Continent Stage	Latitude	Longitude	Angle[1]
A. Laurentia			
Tremadoc	-15.70	43.10	86.70
Arenig	3.02	41.64	75.51
Lland.-Car.	26.40	39.70	71.40
Ashgill	21.00	41.20	71.60
B. Baltica			
Tremadoc	-19.00	77.00	128.0
Arenig	-15.31	77.68	113.4
Lland.-Car.	-10.70	78.50	98.40
Ashgill	-9.20	72.30	88.50
C. Siberia			
Tremadoc	8.10	56.20	130.1
Arenig	13.59	57.63	124.60
Lland.-Car.	19.66	59.30	119.30
Ashgill	24.40	60.70	115.70
D. Gondwana			
Tremadoc	-6.10	86.70	152.50
Arenig	-2.66	84.32	138.90
Lland.-Car.	1.30	81.60	124.90
Ashgill	-3.40	85.50	110.60

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[1] All rotations follow right-hand rule, i.e., positive counter-clockwise


Panthalassic Ocean
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Iapetus Ocean
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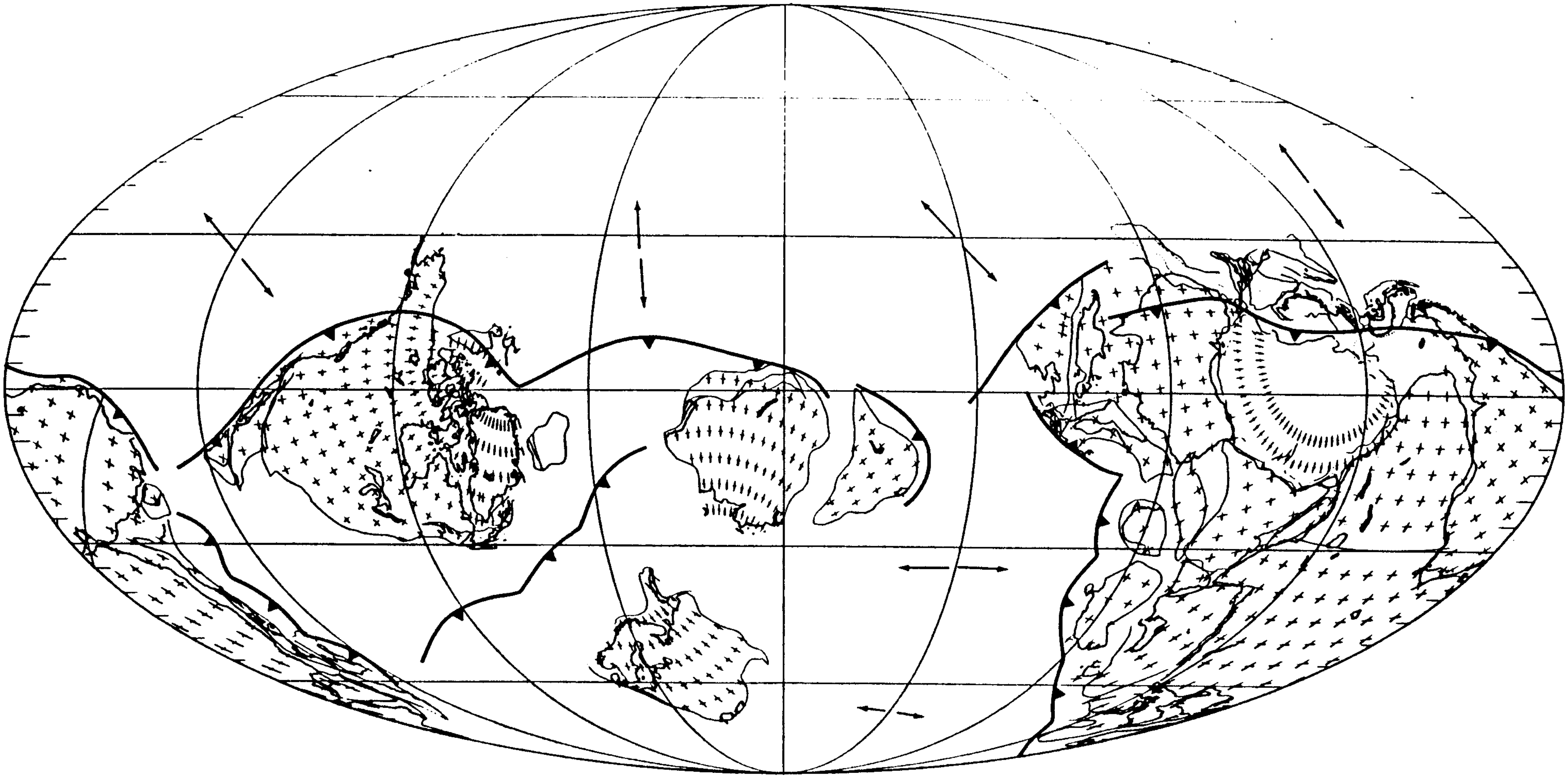
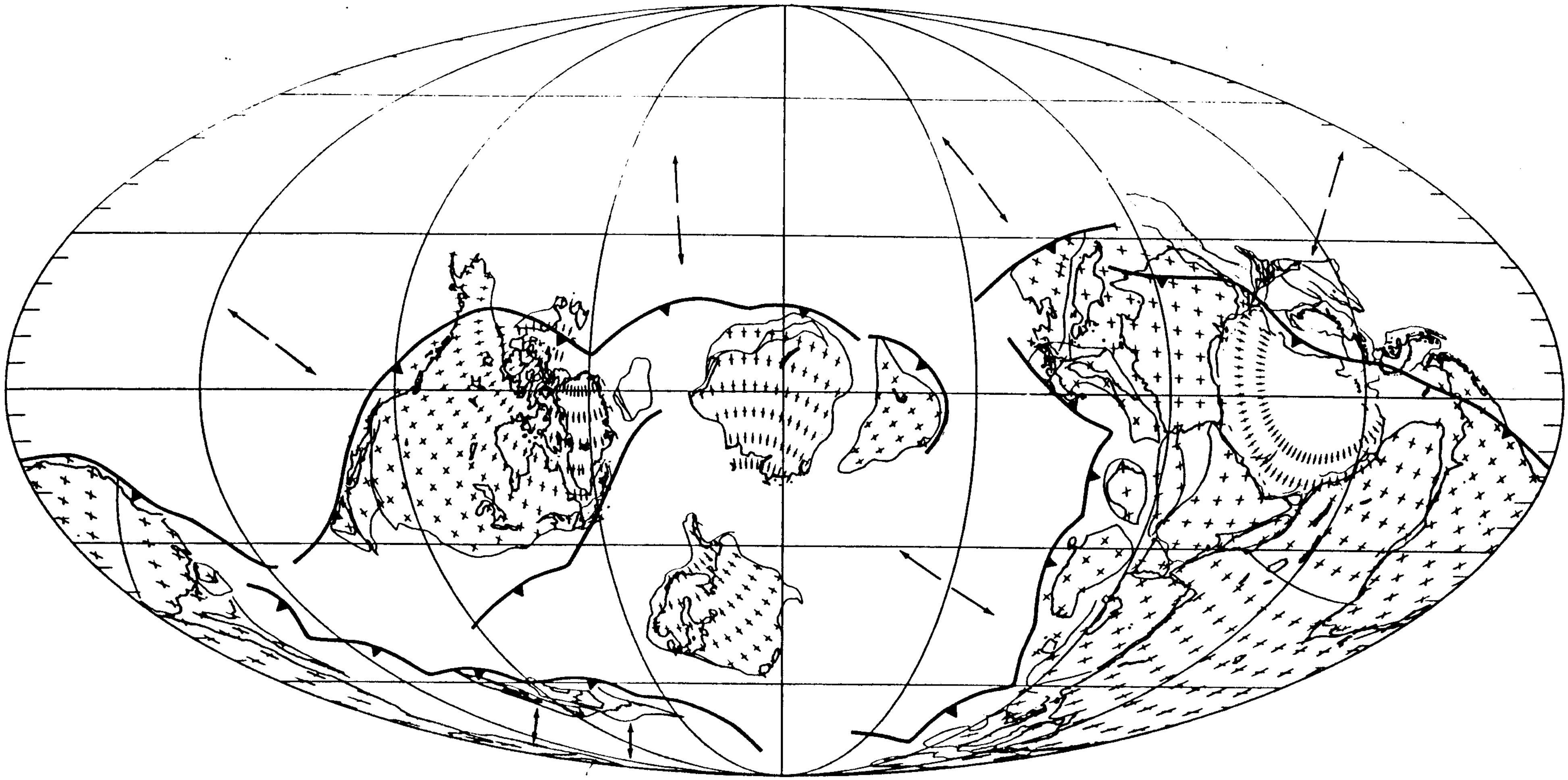
ENG
Baltica
Siberia
YU
PD
Paleotethys Ocean
SC
Gondwana
TR
cc
Kaz.
SC
IR
IN
QT
BM
GI
NC
qq
Equator
pap
tt
SNZ
NNZ
Panthalassic Ocean



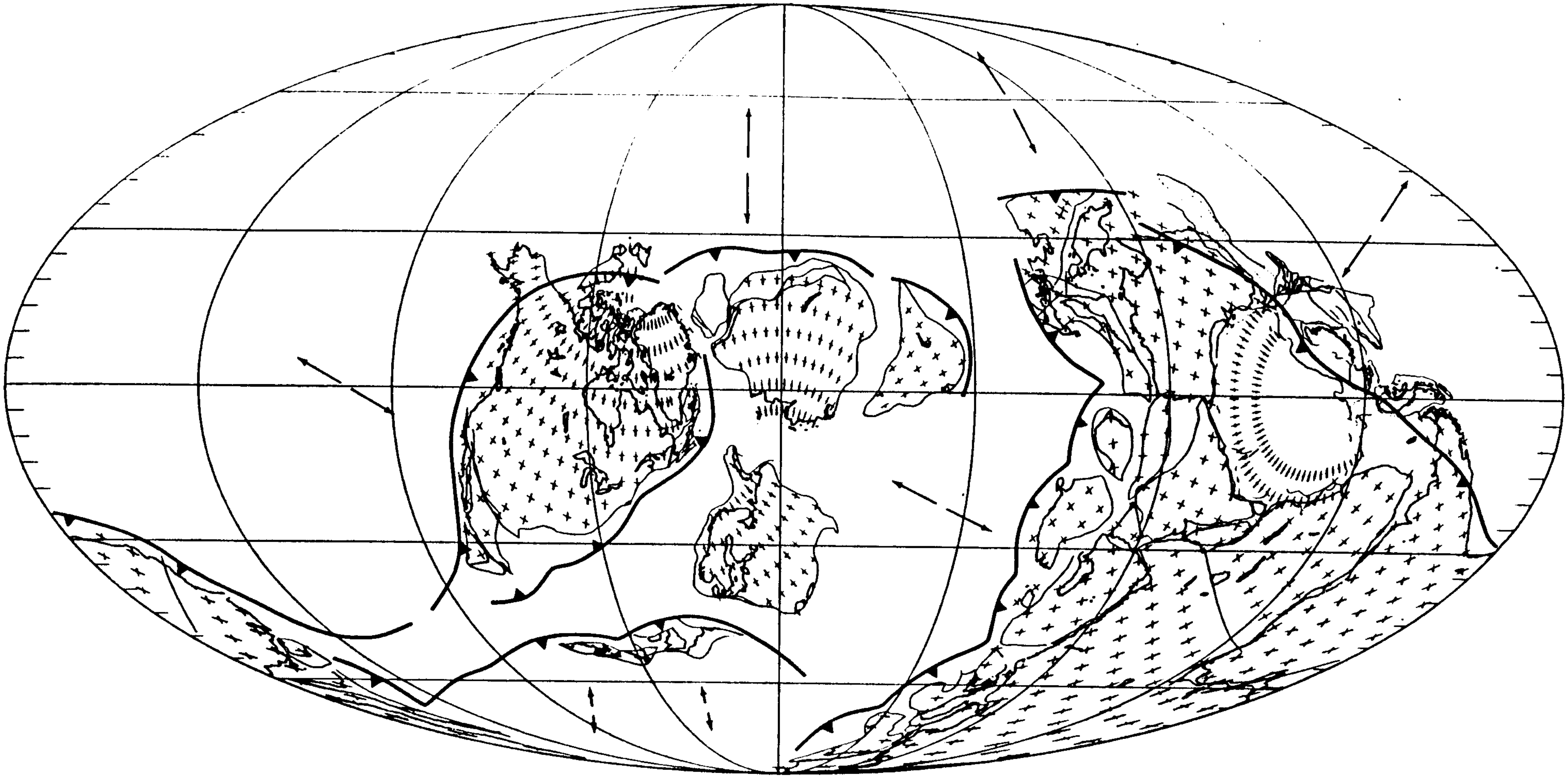
Earliest Ordovician (Tremadoc)

Figure 2



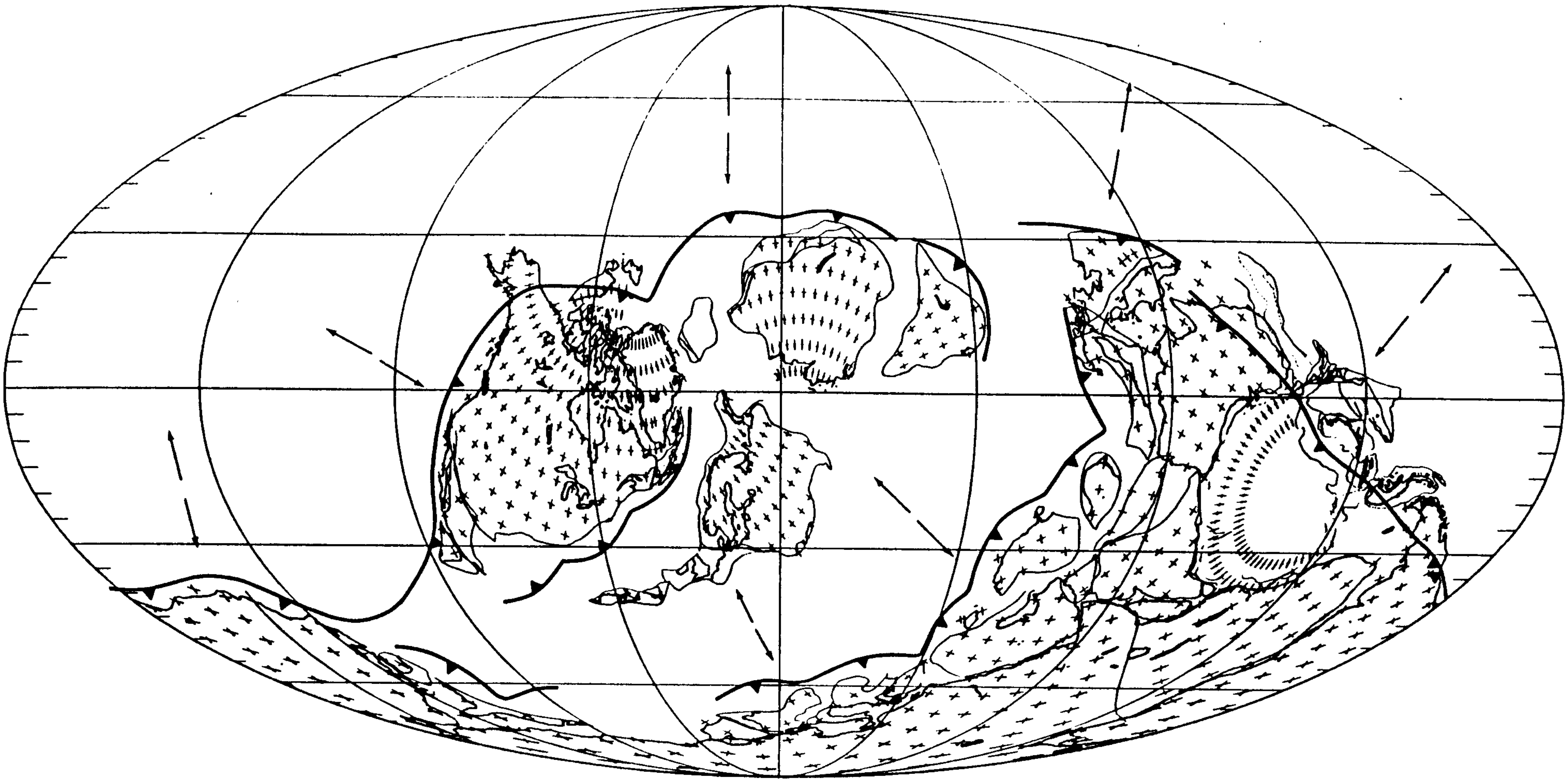
Early Ordovician (Arenig)

Figure 2



Middle–Late Ordovician (Llandeilo–Caradoc)

Figure 4



Late Ordovician (Ashgill)

Figure 5