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NORTH WEST SHELF PROJECT
Palaeomagnetic Framework

Phanerozoic configurations of Greater Australia: Evolution of the North West Shelf

Part One
Review of reconstruction models

by

Chris Klootwijk

AGSO Record 1996/51

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REVIEW OF RECONSTRUCTION MODELS

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Chris Klootwijk

DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

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CONTENTS

SCOPE

The main purpose of this three-part review is to summarise and evaluate geological and palaeomagnetic constraints on the former location and dispersal of continental fragments that are believed to have formed part of the northern margin of Greater Australia, sometime during the Phanerozoic. The emphasis is on identification of fragments that were adjacent to Australia's northwestern margin and on their dispersal in relation to its Phanerozoic evolution. The search for such former fragments has been wide, and geographically covers the whole of Asia east of the Urals and terranes in the North American Cordillera.

The review is presented in three parts: (i) a regional, in part historical, overview of hypotheses on the fragmentation of Greater Australia/eastern Gondwana and subsequent accretion of disrupted terranes to the Siberian and North American cratons (this Record 1996/51); (ii) compilation of available Phanerozoic palaeomagnetic constraints for the main ***dispersive*** Gondwanan fragments - Australia and India, the main ***accretionary*** craton - Siberia, and all terranes of suspected Gondwanan origin in Asia east of the Urals and in the North American Cordillera. These data are interpreted in terms of palaeolatitudinal evolutions, times of fragmentations, and palinspastic reconstructions, culminating into an integrated interpretation of the palaeomagnetic findings in terms of regional evolution of Australia's North West Shelf, as known from available literature and established so far from AGSO's North West Shelf project (Record 1996/52 - Klootwijk 1996a); and (iii) documentation of all available relevant palaeomagnetic results (Record 1996/53 - Klootwijk 1996b).

Follows p. 1

PREAMBLE

This review of plate reconstruction models discusses the more popular and more successful evolutionary hypotheses developed over the past decade and a half. The models cover the impressively extensive factual knowledge that has been accumulated from many fields in the earth sciences. It is therefore a, perhaps, humbling experience to realise that whilst there is general agreement on the various Gondwanan fragments that accreted to Laurasia and on the main phases of accretion, that there is very little agreement on the more detailed evolution of these dispersal and accretion processes in space and time. A problem that has emerged from this review is the often uncritical regurgitation of palaeomagnetic interpretations far beyond their use-by date in terms of newly acquired geological detail or new developments in palaeomagnetic techniques. What is now required for significant advances to be made in evolutionary models is the acquisition of high quality data from integrated biostratigraphic, palaeomagnetic and geochronologic studies and interpretations that are based on first-hand knowledge of the dispersing/accreting fragments, of the main dispersive Gondwana cratons, i.e. Greater Australia and Greater India, and of the main accretionary cratons of Laurasia, i.e. the Siberian Platform and the Cathaysian continents.

SETUP

Enormous advances have been made during the past two decades in understanding the accretionary evolution of eastern Asia and North America. The terrane concept has been developed from study of the North American Cordillera. China has opened up to the west and knowledge of huge advances in understanding of Chinese geology has become widely available. Sophisticated plate tectonics interpretations of the evolution of the former Soviet Union have been formulated by Russian scientists such as Zonenshain and Khramov. Study of the geology of Southeast Asia has exploded, driven in part by expanding exploration interests. Paul Tapponnier's formulation of the propagation extrusion model, featuring India's indentation of Asia, has revolutionised understanding of deformation tectonics driven by far-field stresses. Global and large-scale regional plate tectonic interpretations have become common place, facilitated by widespread availability of geological databases and global reconstruction software. Palaeomagnetic techniques and interpretations have become highly sophisticated and the global palaeomagnetic database has grown into a most useful repository of data. With this explosion of knowledge a plethora of regional geological interpretations and evolutionary hypotheses has been published. For a confined and accessible overview, emphasis is placed on interpretations and hypotheses that are of historical or current significance. Studies of lesser regional significance or impact are addressed only where relevant detail is added to the overview. Where possible the studies are summarised in chronological order as to emphasise the evolution of concepts.

Stratigraphic and tectonic studies of major impact or historical significance

- Burrett
- Şengör
- "Chicago group": Scotese, Rowley, Nie Shangyou, Ziegler
- Metcalfe
- Zonenshain
- IGCP Project 283 "Geodynamic Evolution of Paleoasian Ocean"
- Geodynamic evolution of China
- Gondwanan terranes: North American Cordillera, northeastern and northern Russia

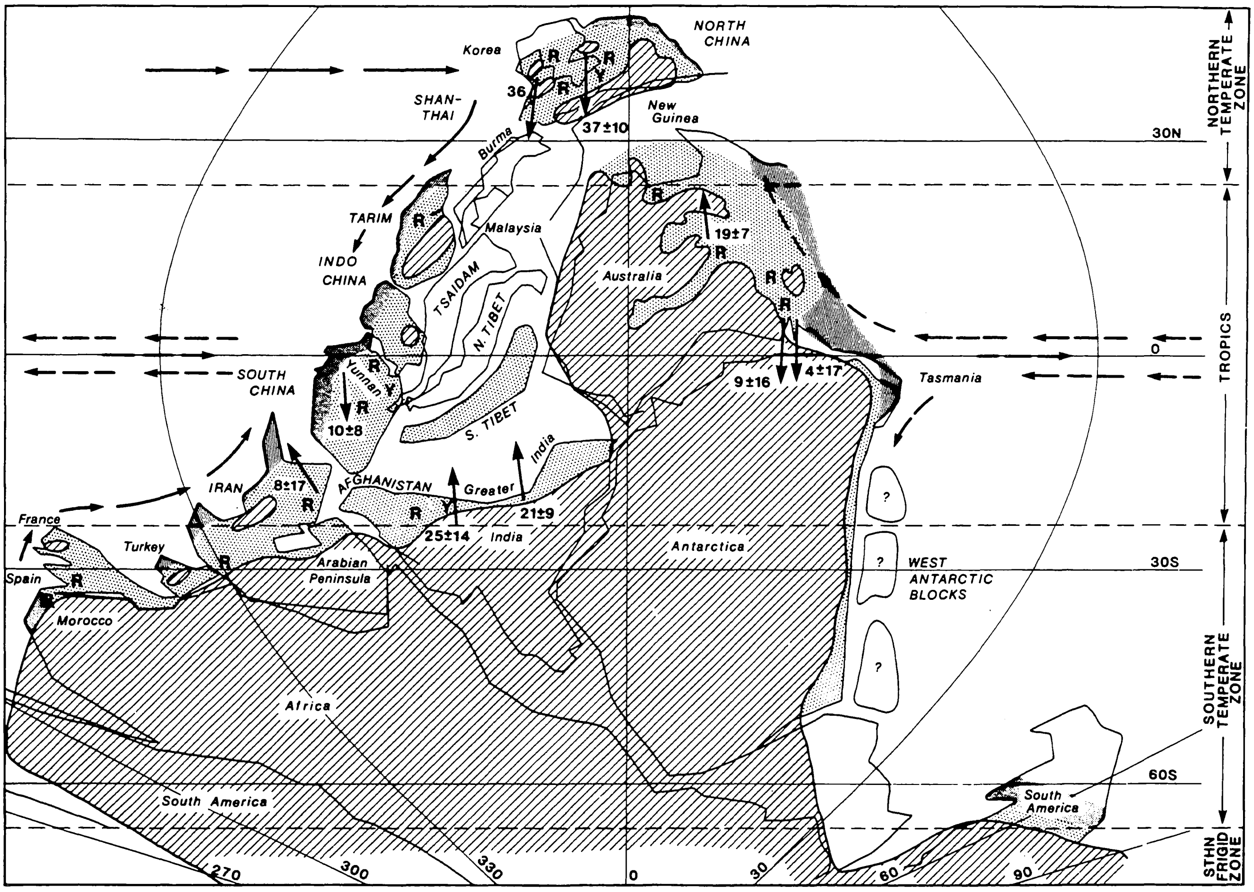


Figure 1 Late Early Cambrian reconstruction after Burrett et al. (1990, fig.3). Arrows with numbers are palaeomagnetic declinations, numbers are palaeolatitudes with errors. Dashed arrows are warm ocean currents, solid arrows are cold currents. Longitude values are arbitrary.

Stratigraphic and tectonic studies of more confined significance

- Young
- Audley Charles
- Helmcke
- Hutchinson

Palaeomagnetic syntheses

- Li Zheng Xiang and coworkers (UWA)
- Zhao and coworkers (University of California at Santa Cruz)

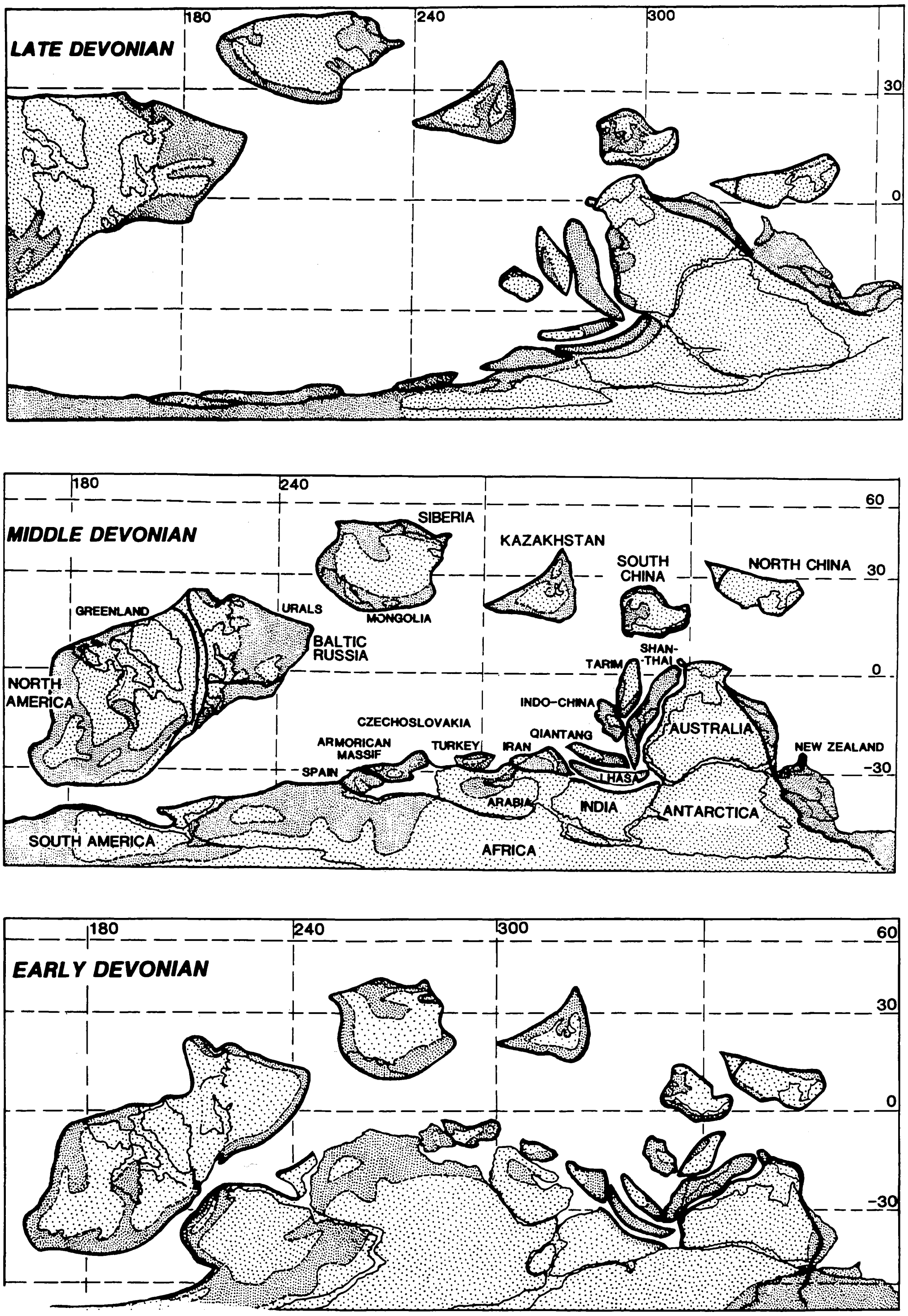


Figure 2 Palaeogeographic maps for the Devonian after Burrett et al. (1990, fig.6). The reconstructions are based on vertebrate distributions and palaeomagnetic and lithostratigraphic constraints. Land: soft stipple, shallow epicontinental seas: heavy stipple. Major terrane boundaries in heavy lines.

STRATIGRAPHIC AND TECTONIC STUDIES OF MAJOR IMPACT OR HISTORICAL SIGNIFICANCE

Burrett

Burrett was one of the first authors after Argand (1924) to revive the concept of Asia as a continental collage (Burrett,1974). He originally defined boundaries of nine major blocks, i.e. Northern Europe, Siberian Platform, Jano-Kalymia (Kolyma), Kazakhstan, Tarim, North China, South China, Southeast Asia and India, on the basis of orogenic belts and faunal province boundaries and suggested a fusion chronology based on palaeogeographical, palaeontological and tectonic evidence. Although ideas about such boundaries are now more refined, blocks further subdivided, and fusion timings updated, some of his early opinions are still much worth highlighting: e.g. contiguity of the Jano-Kolyma block with the collage of terranes in the North American Cordillera; progressive accretion during the Palaeozoic of the Altaids to the Siberian platform; collision of Kazakhstan and the Siberian Platform in the Late (middle) Carboniferous; Early Permian collision of the Tarim block and Kazakhstan; Mid Triassic - Carnian to Norian - collision of Southeast Asia and South China; collision of the North and South China blocks as late as Early Jurassic rather than during the Norian (Indosinian Orogeny).

Subsequent collaboration with Stait and Long culminated in another leading paper (Burrett et al.,1990), summarising earlier obtained faunal constraints on palaeogeographic reconstructions and timings of dispersion and accretion (Burrett and Stait,1985,1986; Long and Burrett,1989). Early Cambrian and Devonian reconstructions are reproduced here as Figures 1 and 2. It is a minor shortcoming that the reconstructions are presented in a palaeolatitude framework that is open to question on account of uncritical acceptance of palaeomagnetic data. Burrett and coworkers postulate contiguity of the Shan-Thai (Sibumasu) terrane and northwestern Australia from strong similarities in Late Cambrian trilobites and Ordovician mollusc, stromatoporoid, brachiopod and conodont faunas. Microvertebrate and conodont evidence indicates that close proximity persisted at least till the Late Devonian. New evidence for a glacigenic origin of the Phuket Group in Thailand (Burrett et al.,1991) indicates that contiguity with a southpolar Australia was maintained during at least the Late Carboniferous-Early Permian. Permian to Middle Triassic deep-water deposits in the suture zone separating the Shan-Thai terrane from the Indochina terrane suggest a Late Triassic collision between the two terranes. Late Devonian shared biotic assemblages between North China, South China and Australia are interpreted in support of close continental proximity of these three major blocks. The remarkable degree of endemism in Devonian vertebrate faunas from South China is interpreted as a palaeogeographic/palaeoclimatic effect, with South China's position reconstructed near to the northwestern Himalayas, and with North China's position off northern Australia. It should be noted that the Early Cambrian and Devonian reconstructions (Figs 1,2) show different relative positions for the South and North China blocks versus Australia, without any mention in the paper how and why this interchange has come about.

Šengör

Šengör has addressed the problem of the "Tethyan Paradox" in several seminal synthesis papers on the evolution of the Tethysides (Šengör,1979,1984,1985). By the late seventies and early eighties plate reconstructions based on rigid body rotations (e.g. Smith,1971,1973) had postulated the existence of a wide eastward opening "Tethys" between Laurasia and Gondwana(land: Šengör insists "Gondwanaland" is the proper term to use) for periods as far back as the Late Carboniferous and Permian. At that time, however, no field evidence had been established for existence of an oceanic basin

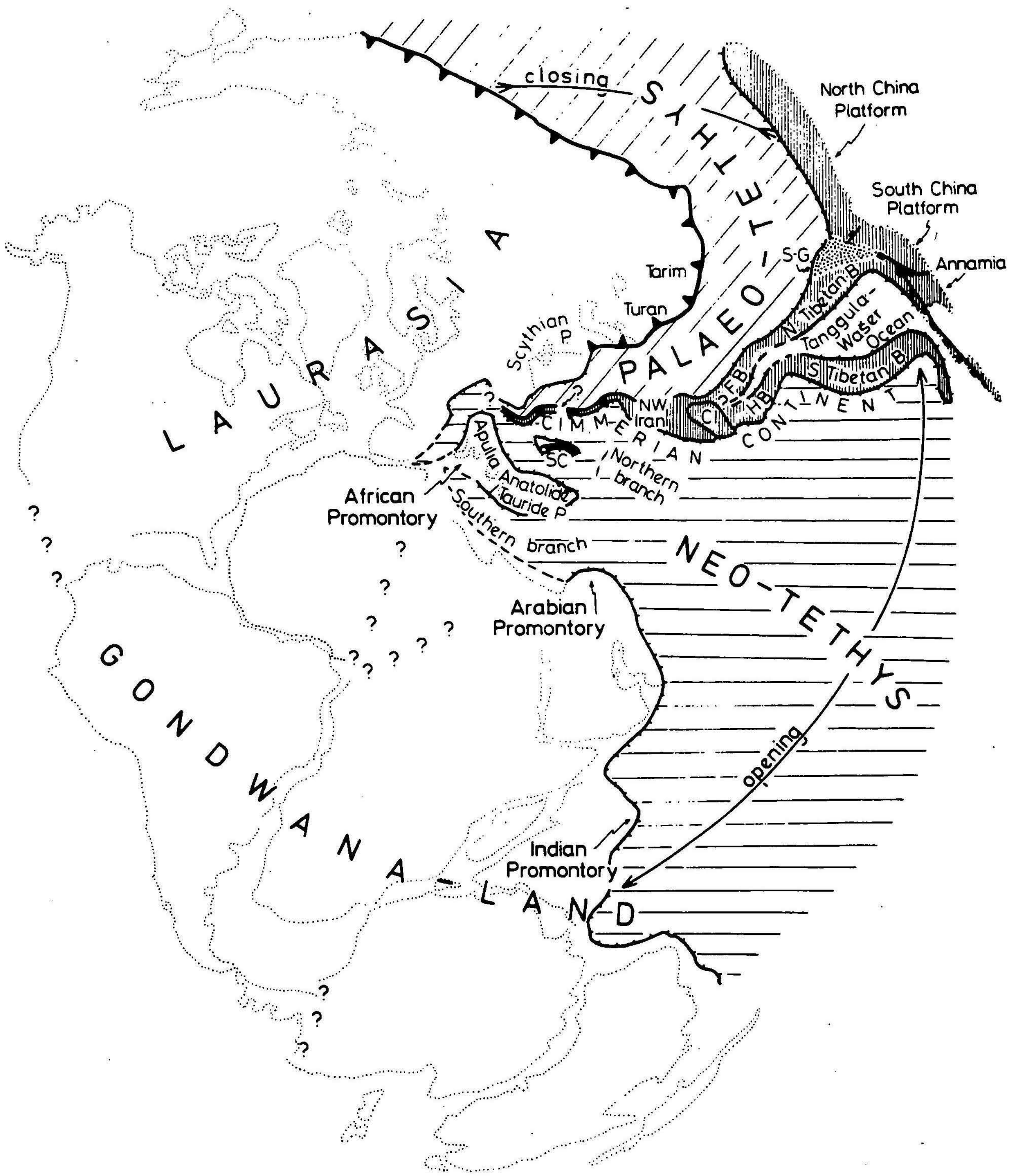


Figure 3 The Liassic Pangea and Tethyan domain with schematic indication of the Cimmerian Continent, the Palaeo-Tethys and the Neo-Tethys, after Şengör (1984, fig.6). SC= Sakarya Continent; FB= Farah Block; HB= Helmand Block sensu lato.

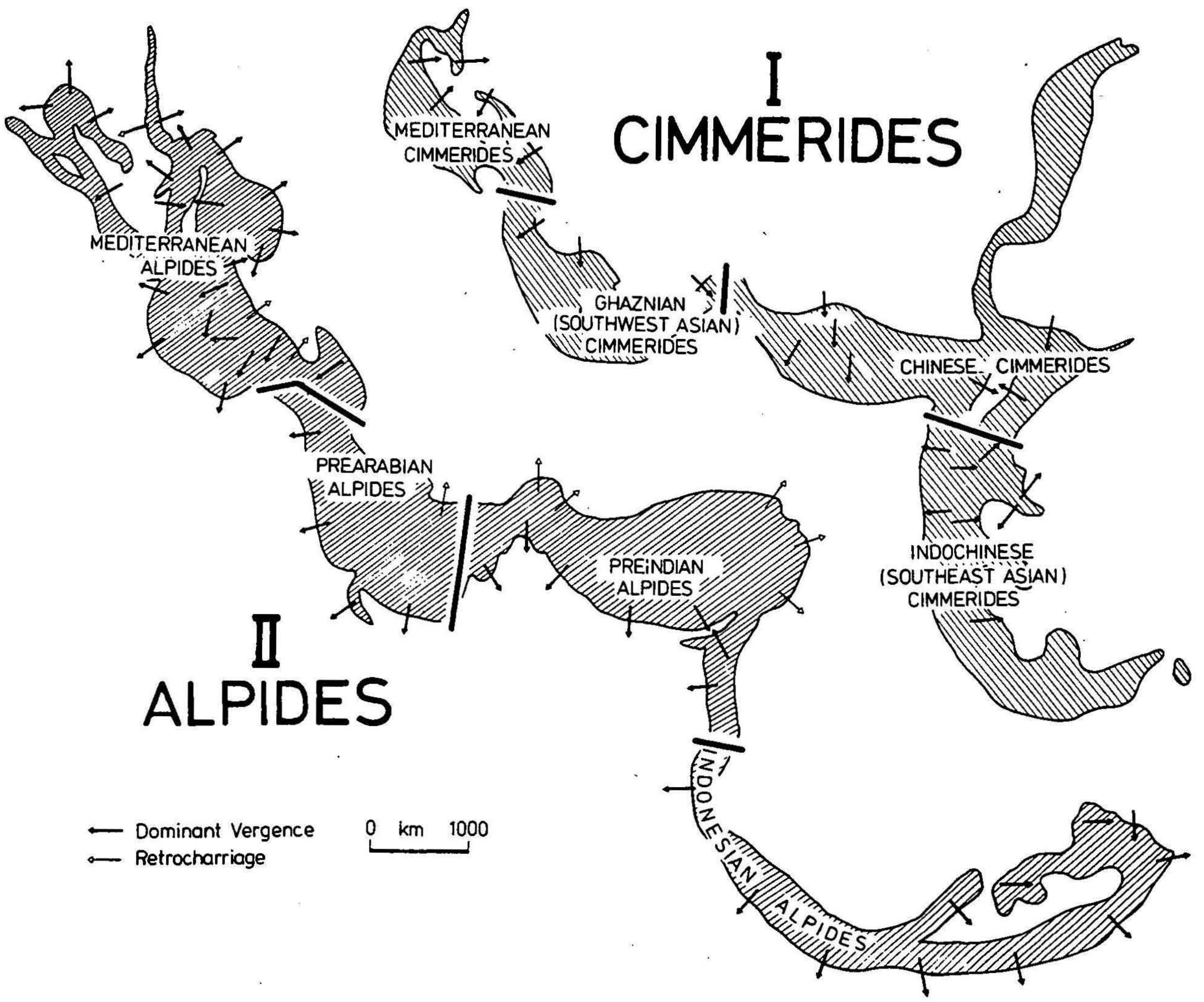


Figure 4 Schematic extent of Cimmeride and Alpide orogenic zones (i.e. "alpinotype" Cimmerides and Alpides) and their longitudinal subdivisions, after Şengör (1984, fig.7B). Also shown are the dominant directions of main vergence and reverse vergence (rétrocharriage). In nearly all cases illustrated, the main vergence and orogenic polarity are co-directional. The shape of the alpinotype Cimmerides gives little idea of the "original" shape of the orogen, which must have undergone very large strains during the later Alpide deformations. The figure emphasises that the Alpine-Himalayan mountain ranges consist of two distinct, largely independent, orogens that are superimposed.

during the Permian and Early Triassic in the more western part of the Alpine-Himalayan System of the Northern Tethys region (e.g., Mennessier,1972; Stöcklin,1974,1983,1984; Crawford,1974; Bassoullet et al.,1980; Smith,1988), albeit Late Devonian to Early Carboniferous ophiolites and deep water sediments were found in a possible suture zone through Iran, Afghanistan, the Pamirs, Tibet, Yunnan, Thailand and Malaysia (Stöcklin,1984). In a masterly synthesis of literature and field data, Şengör postulated that the Alpine-Himalayan System consists in fact of two independent, but largely superimposed, orogenic complexes. The older Cimmerides Complex formed between Early Carboniferous and Early Cretaceous, through destruction of the Palaeo-Tethys, the original eastward-widening oceanic basin between Laurasia

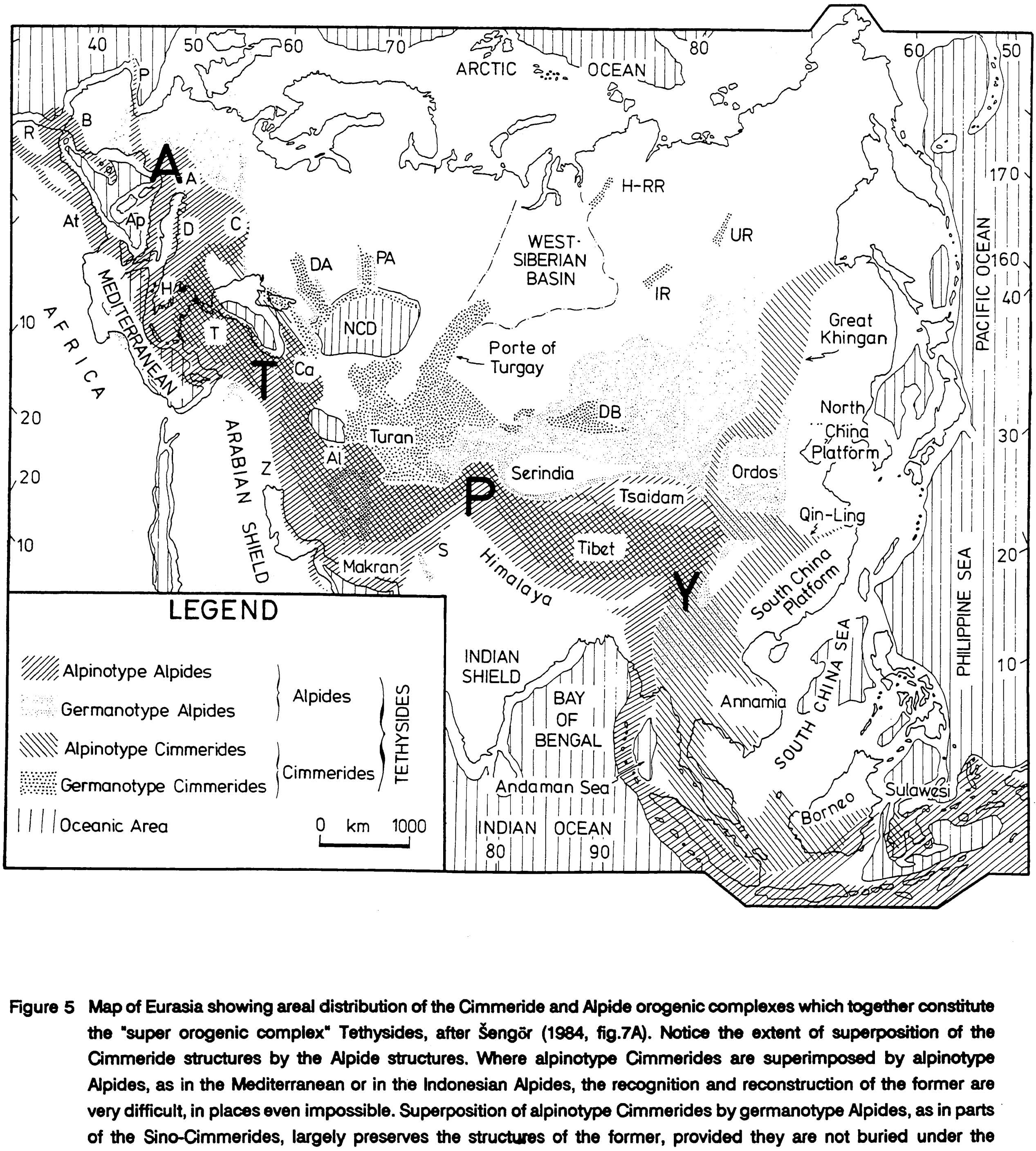
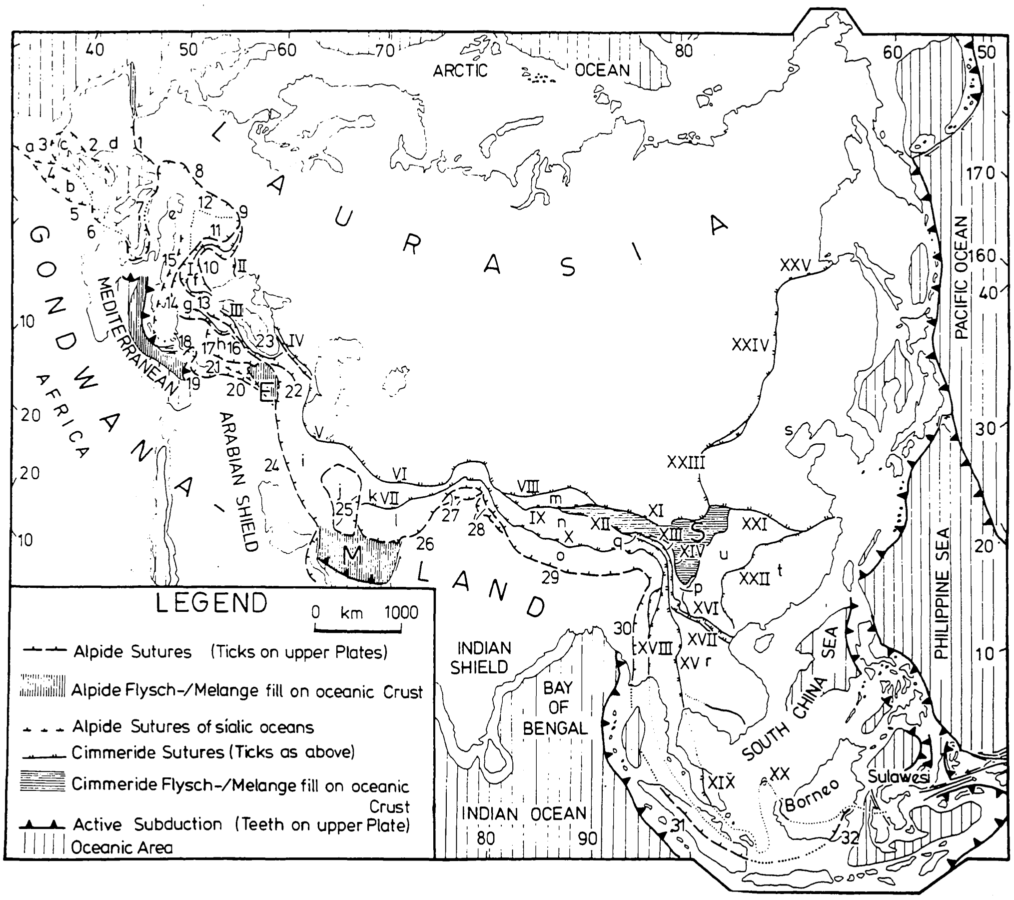


Figure 5 Map of Eurasia showing areal distribution of the Cimmeride and Alpide orogenic complexes which together constitute the "super orogenic complex" Tethysides, after Şengör (1984, fig.7A). Notice the extent of superposition of the Cimmeride structures by the Alpide structures. Where alpinotype Cimmerides are superimposed by alpinotype Alpides, as in the Mediterranean or in the Indonesian Alpides, the recognition and reconstruction of the former are very difficult, in places even impossible. Superposition of alpinotype Cimmerides by germanotype Alpides, as in parts of the Sino-Cimmerides, largely preserves the structures of the former, provided they are not buried under the sediments associated with the germanotype tectonism. Superposition of the germanotype Cimmerides by the germanotype Alpides frequently produces the effect of "long-lived structures" subject to repeated "posthumous" reactivations. Key to large letters: A= Alpine Syntaxis; T=Turkish Syntaxis; P=Pamir Syntaxis; Y=Yunnan Syntaxis. Key to smaller letters: A=Alps; Al=Alborz; Ap=Apennines; At=Atlas; B=Betics; C=Carpathians; Ca=Caucasus; D=Dinarides; DA=Donetz Aulacogen; H=Hellenides; H-RR=Hantaj-Rybninsk Rift; IR=Irkineev Rift; NCD=North Caspian depression; P=Pyrenees; PA=Pachelma Aulacogen; R=Riff; S=Suleiman Ranges; T=Turkish Ranges; Z=Zagros.

and the northward and counterclockwise moving Cimmerian Continent. The younger Alpides Complex formed by partial closure of the Neo-Tethys through the northward and counterclockwise movement of individual Gondwanan fragments upon Late Jurassic and subsequent breakup of Gondwana (Šengör,1984: figures 6,7B; Figs 3,4). The Neo-Tethys, then generally known as Tethys was identified as the oceanic basin created between the northward moving Cimmerian (ribbon-) Continent and Gondwana. Onset of Neo-Tethyan subduction occurred during the Aptian-Albian. Šengör (1987) defines any suture closed at that time as Cimmeride in origin.

The accreting Cimmerian (ribbon-) Continent incorporated, and further tectonised, earlier Hercynian structures. The Cimmerian Continent was itself heavily tectonised upon later accretion of Gondwanan fragments that subsequently formed the Alpides complex. This, and the limited width of the Cimmerides Complex west of eastern Asia probably led to the perceived absence of evidence for pre-Triassic (non-Alpine) ophiolite complexes and other suture indicators that could mark Cimmeria's accretion. The effects of deformation during both accretion phases extended throughout southern Laurasia, way beyond the accreted complexes. Šengör (1984,1985) identifies and describes in some detail the extent of the Cimmerian and Alpine fragments of the Tethysides and also of the regions of southern Laurasia that were tectonically affected during both accretion phases (Šengör,1984: figure 7A; Fig.5). Following the classical German school he describes the former as Alpinotype Cimmeriden and Alpiden and the latter as Germanotype Cimmeriden and Alpiden. He also provides a detailed description of block boundaries and sutures and likely ages of accretion (Šengör,1984: figure 21; Fig.6). In the context of this review some of his interpretations regarding evolution of accretionary deformation of the Cimmeriden are worth highlighting:

- Separation of the Cimmerian Continent from Gondwana began in the Late Permian (Šengör et al.,1988) and occurred mainly during the Triassic (Šengör,1987), although rifting started earlier in the easternmost parts;
- The North China block, the South China (Yangtze and Huanan) block, the eastern part of the Qiangtang block and Indochina had already separated from Gondwana in pre-Late Carboniferous times, possibly during the Devonian (Šengör et al.,1988);
- The outline of the Cimmerian Continent is more complex in the east because of interaction with three independent continental pieces representing the Cathaysian continents: i.e. the North China, South China and Indochina blocks; consequently, to the east of the 100°E meridian the Cimmeride part of the Tethysides is very much enlarged compared with the region to the west;
- Closure of the Palaeo-Tethys occurred between the Middle Triassic and the Late Jurassic along most of its extent.
- The Turan block had docked already with Laurasia by the latest Carboniferous (Šengör,1987);
- Cimmeride deformation in North Afghanistan and the Western Hindu Kush occurred from Early (middle) Carboniferous onwards till Jurassic;
- Cimmeride deformation in the North Pamir began in late Early Carboniferous;
- Accretion of the Tarim block occurred during Late Carboniferous or Early Permian;
- The North China Platform was sutured to the North China Fold Belt during the middle Carboniferous;
- Sutures in the Kunlun between the Qaidam, Tarim and other blocks are of Middle and Late Palaeozoic age (Šengör et al.,1988);
- The Songpan-Ganzi accretionary complex is mainly Triassic in age;
- The Shan-Thai block and its northwestern continuation in the Qiangtang block have Early Permian glacial sediments (Šengör et al.,1988) and were in close proximity to the northwestern margin of Australia in Gondwana, i.e. at least up till this time (Šengör,1985);
- Indochina collided initially with South China along the Song-Ma suture during the middle Carboniferous (Tournaisian-Visean) (Šengör,1984,1985). The slightly further south located Song Da suture indicates renewed contact during the Late Triassic, after a speculative earlier dispersion;
- The South China block may consist of two fragments accreted during the Jurassic;



Cimmeride Sutures:
I—Main Paleo-Tethyan Suture in the Balkan/Carpathian Cimmerides
II—North Dobrudja Suture
III—Main Paleo-Tethyan Suture in the Anatolian Cimmerides (the Karakaya Suture, which lies in block g, is not assigned a number)
IV—Main Paleo-Tethyan Suture in the Caucasus
V—Talesh-Mashhad Suture
VI—Paropamisus-Hindu Kush-Northern Pamir Suture
VII—Waşer Suture
VIII—Northern Synclinorium of western Kuen-Lun
IX—Southern Synclinorium of western Kuen-Lun
X—Tanggula Suture
XI—Anyemaqen Shan Suture
XII—Lantanjiang Suture
XIII—Jingshajiang Suture
XIV—Litang Suture
XV—Dien-Bien-Phu Suture
XVI-Song Da (Black River) Suture
XVII—Song Ma (Red River) Suture
XVIII—Sittang Valley-Myitkyina Zone Suture
XIX—Medial Malaya Zone Suture
XX—Natuna Suture
XXI—Qin-Ling Suture
XXII—Mid-South China Platform Suture (Hsü's conjectured suture)
XXIII—West Ordos Suture
XXIV—Great Khingan Suture
XXV—Shilka Zone Suture

Alpide Sutures:
1—Pyrenean Suture
2—Betic Suture
3—Riff Suture
4—High Atlas Suture
5—Saharan Atlas Suture
6—Kabylian Suture
7—Apennine Suture
8—Alpine Suture
9—Pieniny Klippen Belt Suture
10—Circum-Moesian Suture ("Mesoparatethys" of Grubiç, 1974).
11—Mureş Suture
12—Hypothetical "Intra-Pannonian Belt" Suture of Channel *et al.* (1979)
13—Intra-Pontide Suture
14—Vardar-İzmir-Ankara Suture
15—Pindos-Budva Suture
16—Erzincan Suture
17—Inner-Tauride Suture
18—Antalya Suture
19—Cyprus Suture
20—Assyrian Suture
21—Maden Suture
22—Sevan-Akera Suture
23—Slate-diabase Zone Suture
24—Zagros Suture
25—Circum-Central Iranian Microcontinent Suture
26—Waziristan Suture
27—Kohistan Sutures
28—Ladakh Sutures
29—Indus-Yarlung-Zangbo Suture
30—Burma Suture
31—Mid-Sumatran Suture
32—Meratus Suture

Tethyside Blocks:
a) Moroccan Meseta
b) Oran Meseta
c) Alboran Fragment
d) Iberian Meseta
e) African Promontory
f) Rhodope-Pontide Fragment
g) Sakarya Continent
h) Kırşehir Block
i) Northwest Iran
j) Central Iranian Microcontinent
k) Farah Block
l) Helmand Block *sensu lato*
m) Western Kuen-Lun Central Meganticlinorium
n) North Tibetan Block (Qangtang Block)
o) South Tibetan Block (Lhasa Block)
p) Shaluli Shan Arc
q) Chola Shan Arc
r) Annamia Block
s) North China Platform
t) Southeastern South China Block
u) Sichuan Block

Figure 6 **Terrane/block and suture map of the Tethysides, after Şengör (1984, fig.21). The Cimmeride sutures are indicated with Roman numerals, and the Alpide sutures with Arabic numerals. The terranes/blocks enclosed by them are indicated with letters.**

- Accretion of the North China block may have progressed from southwest to northeast, from (Triassic?) Early Jurassic to Early Cretaceous;
- By the Late Triassic all "Chinese" blocks except the Lhasa block and Indochina had collided with each other and with Laurasia (Šengör et al.,1988);
- In Late Triassic to Middle Jurassic times, most of the major Cimmeride collisions became completed;
- Late Palaeozoic faunal provinces (Šengör,1985: figure 6; Fig.6) are distinct to the main blocks identified in southern and eastern Asia. Thus the Cathaysian flora is restricted to North China - with the notable exception of an Angaran flora in its northern part - to South China, Qiangtang, and Indochina (Šengör,1984,1985), and also to the Arabian Peninsula and Iran (Šengör et al.,1988). Apart from the above exception, the Angaran flora is typical for Laurasia and the Gondwanan flora is typical for the Indian subcontinent and possibly for parts of the southern Tibetan Lhasa block (Šengör,1984,1985; Šengör et al.,1988);
- Large-scale strike-slip faults may have considerably added to the geological complexity of the region;
- None of the Cimmerian sutures is currently active;
- More than 90% of continental fragments within the Tethysides is regarded as Cimmerian in origin (Šengör,1987);
- Šengör (1987) refutes Rowley et al.'s (1985) suggestions that the Lhasa block rifted from northwest Australia in the Late Jurassic, and suggests dispersal at that time for the Mount Victoria Land block instead;
- Šengör (1987) relates the large-scale and persistent northward migration of Gondwanan continental fragments to a hypothetical first-order convective circulation in the upper mantle;
- Šengör et al. (1988) noted that "ribbon continents" are also abundant in the structure of the Altaids (see also Šengör et al.,1993) and suggests that such ribbon continents may play an important role in the evolution of continental collages.

Šengör (1987) notes that the Late Palaeozoic sutures summarised above are not Cimmeride in the strict sense, but for reason of their location within the Cimmeride orogenic zone, and for want of better knowledge, they are so classified. In the section on palaeomagnetic analysis in part two of this review (Record 1996/52) an attempt is made to relate such accretion to a middle Carboniferous northward excursion of eastern Gondwana and subsequent contact with the Altaids, and to reinstate this accretion as the Variscan (Hercynian) process as it was commonly identified previously.

A remarkable and questionable aspect of the original Cimmerian Continent concept is the rather undisturbed state of the ribbon continent crossing the wide open Palaeo-Tethys (Šengör,1984: figure 7B Fig.4). It is unclear what processes led to its separation from Gondwana, other than back-arc formation of the Neo-Tethys (Šengör,1979) which must have acted uniformly over the about 10,000 km margin of Gondwana stretching from the eastern Carpathians to northern Australia (Šengör,1984: figure 7A; Fig.5). How could such a ribbon continent have crossed the Palaeo-Tethys without evident marine incursions, apart from the Waser-Banggong Co-Nu Jiang ocean or Meso-Tethys of Belov et al. (1986) which is in part represented by the Lhasa-Qiangtang suture? How have all the original palaeogeographic relationships remained intact in the drawn-out process of separation from Gondwana through to accretion to Laurasia? Such conditions are far more likely to have been met if the ribbon continent was transported as an integral part of Gondwana's northern rim, with Gondwana acting as a carrier in crossing the Palaeo-Tethys in part or for its full extent. This aspect will be addressed in some detail in part two of this review (Record 1996/52), in the palaeomagnetic section on the New England Apparent Polar wander Path (APWP). It is fair to say that in subsequent papers, Šengör (1987) has abandoned his original idea of a ribbon continent in favour of a more fragmented dispersal and accretion process (Fig.8) which bears resemblance to Scotese's reconstructions. Without much description or justification of these global reconstructions, Šengör positions the Shan-Thai and Mount Victoria Land blocks opposite northwestern Australia as part of the Cimmerian Continent still attached to northern Gondwana by the Late Permian (Fig.8A). The Early Triassic reconstruction (Fig.8B) shows Cimmeria drifting away, with Mount Victoria Land still near to the southern part of northwestern Australia. The Late Jurassic

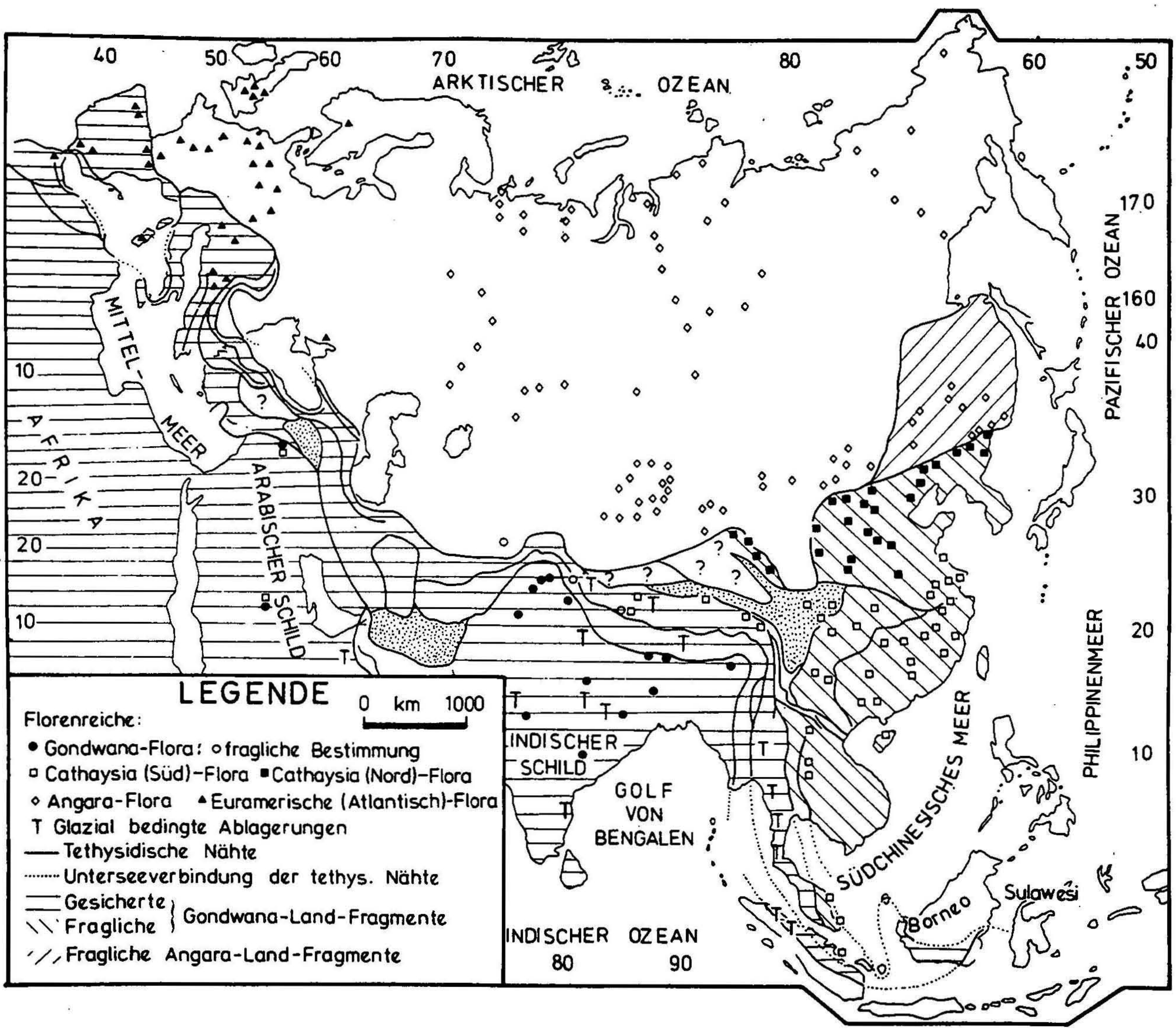


Figure 7 Schematic overview of Late Palaeozoic Eurasian floral provinces, after Şengör (1985, fig.6).

reconstruction (Fig.8C) shows Mount Victoria Land drifting away together with the Cimmerian Continent, whereas the Cathaysian continents - North China, Yangtze block, Huanan block and Indochina - are accreted already to Laurasia. Unfortunately, no maps are shown defining the Palaeozoic location of original Gondwanan fragments which now reside in Asia, with Fig.8A showing that the Cathaysian continents were crossing the Palaeo-Tethys already by the Late Permian.

More recently Şengör has shifted his synthesis interests toward the Altaids complex surrounding the southern part of the Siberian Craton (Şengör et al.,1993,1994). The Altaids contain fragments of suspected eastern Gondwanan origin, such as Kazakhstan and the Tarim (Şengör et al.,1993: figure 1; Fig.9), and are thus of considerable interest for this review. In analysing the evolution of this giant

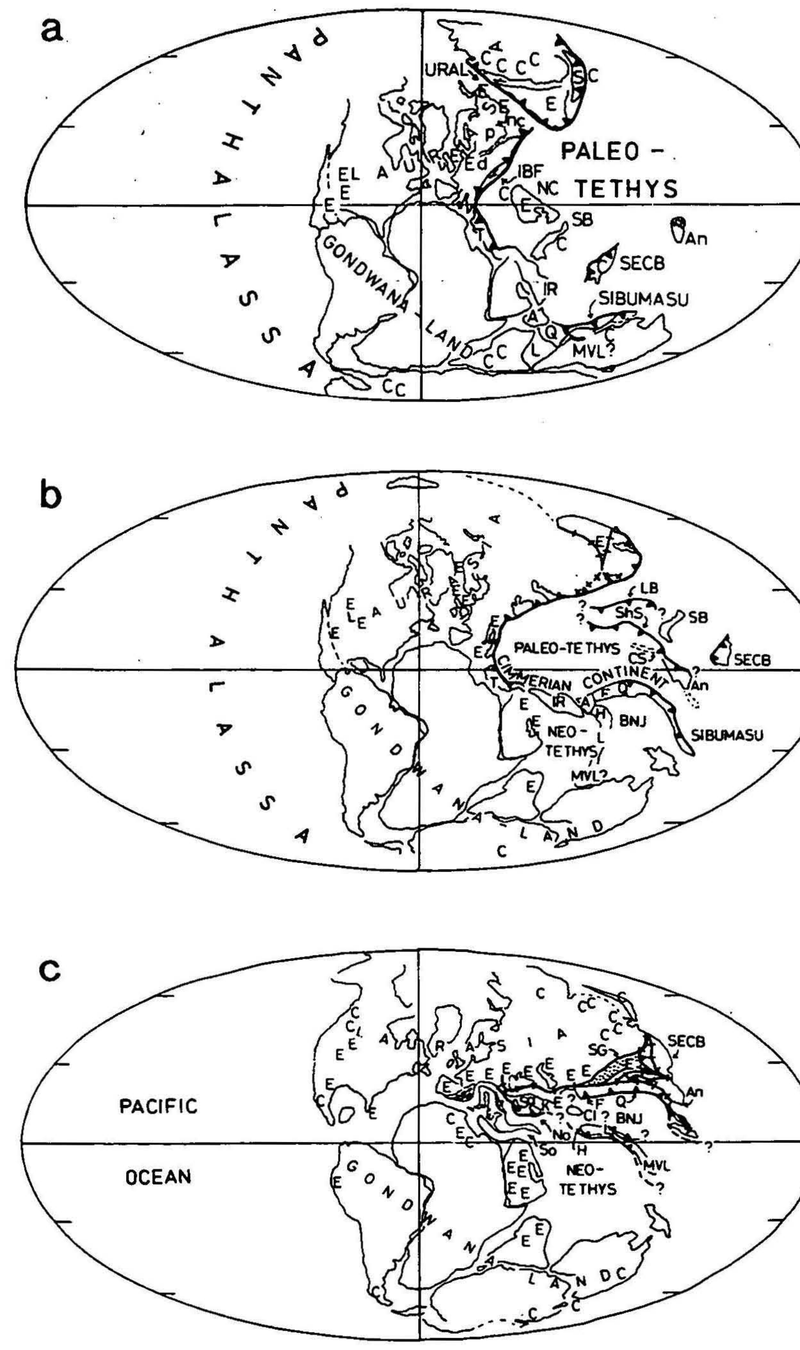
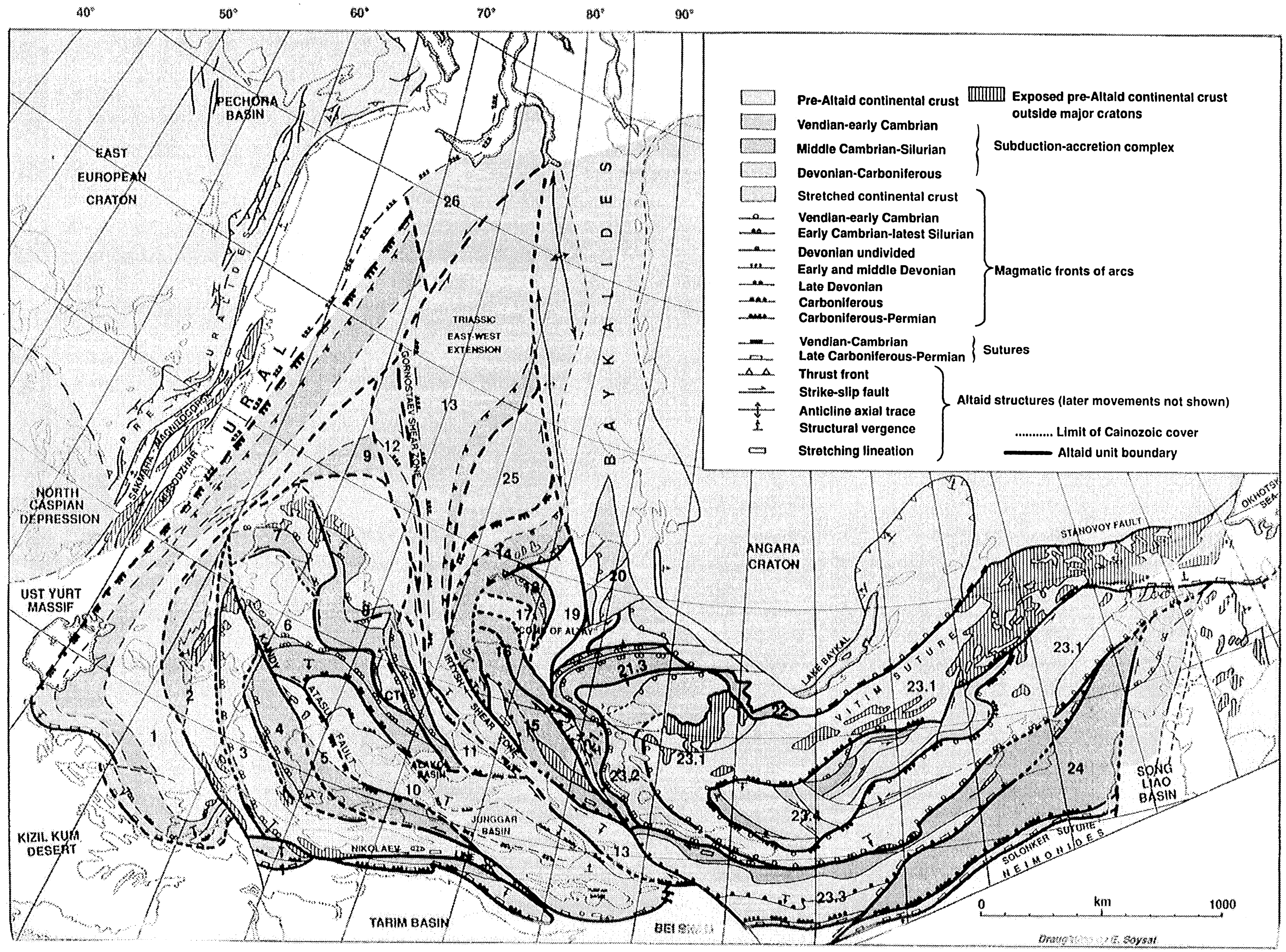


Fig.8 Schematic reconstructions of the evolution of the Tethyan domain for the Late Permian (Kazanian; a), Early Triassic (Induan; b), and the Late Jurassic (Volgian; c), after Şengör (1987, fig.3A-C). Abbreviations of fragments: A=Afghan blocks, An=Annamia, BNJ=Waser-Ushan-Pshart-Banggong Co-Nu Jiang/Mandalay Ocean, CI=Central Iranian microcontinent, CS=Chola Shan, ES=Emei Shan, F=Farah block, H=Helmand block, Hu=Huanan block, IR=Iranian block, L=Lhasa block, MVL=Mount Victoria Land, No=Northern branch of Neo-Tethys, Qu=Quetta-Sibi graben, RRF=Red River Fault, S=Tarim, S'=Pamir-west Qiangtang block, S"=east Qiangtang block, SG=Songpan-Ghazi, Sibumasu=China-Burma-Malaya-Sumatra portion of the Cimmerian Continent, So=Southern branch of the Neo-Tethys.



40°
50°
60°
70°
80°
90°
Pre-Altaid continental crust
Exposed pre-Altaid continental crust outside major cratons
Vendian-early Cambrian
Middle Cambrian-Silurian
Devonian-Carboniferous
Subduction-accretion complex
Stretched continental crust
Vendian-early Cambrian
Early Cambrian-latest Silurian
Devonian undivided
Early and middle Devonian
Late Devonian
Carboniferous
Carboniferous-Permian
Magmatic fronts of arcs
Vendian-Cambrian
Late Carboniferous-Permian
Sutures
Thrust front
Strike-slip fault
Anticline axial trace
Structural vergence
Stretching lineation
Altaid structures (later movements not shown)
Limit of Cainozoic cover
Altaid unit boundary
PECHORA BASIN
EAST EUROPEAN CRATON
NORTH CASPIAN DEPRESSION
UST YURT MASSIF
KIZIL KUM DESERT
URAL
URALIDES
PRE-URAL
MUGODZHAR
SAKMARA
TRIASSIC EAST-WEST EXTENSION
GORNOSTAEV SHEAR ZONE
IRTYSH SHEAR ZONE
BAYKALIDES
ANGARA CRATON
LAKE BAYKAL
VITIM SUTURE
STANOVOY FAULT
OKHOTSK SEA
SONG LIAO BASIN
SOLONKER SUTURE
NEIMONIDES
KARAUL
ATASU FAULT
ALAKOL BASIN
JUNGGAR BASIN
NIKOLAEV
TARIM BASIN
BEI SHAN
CONE OF ALTAY
CT
1
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19
20
21.3
22
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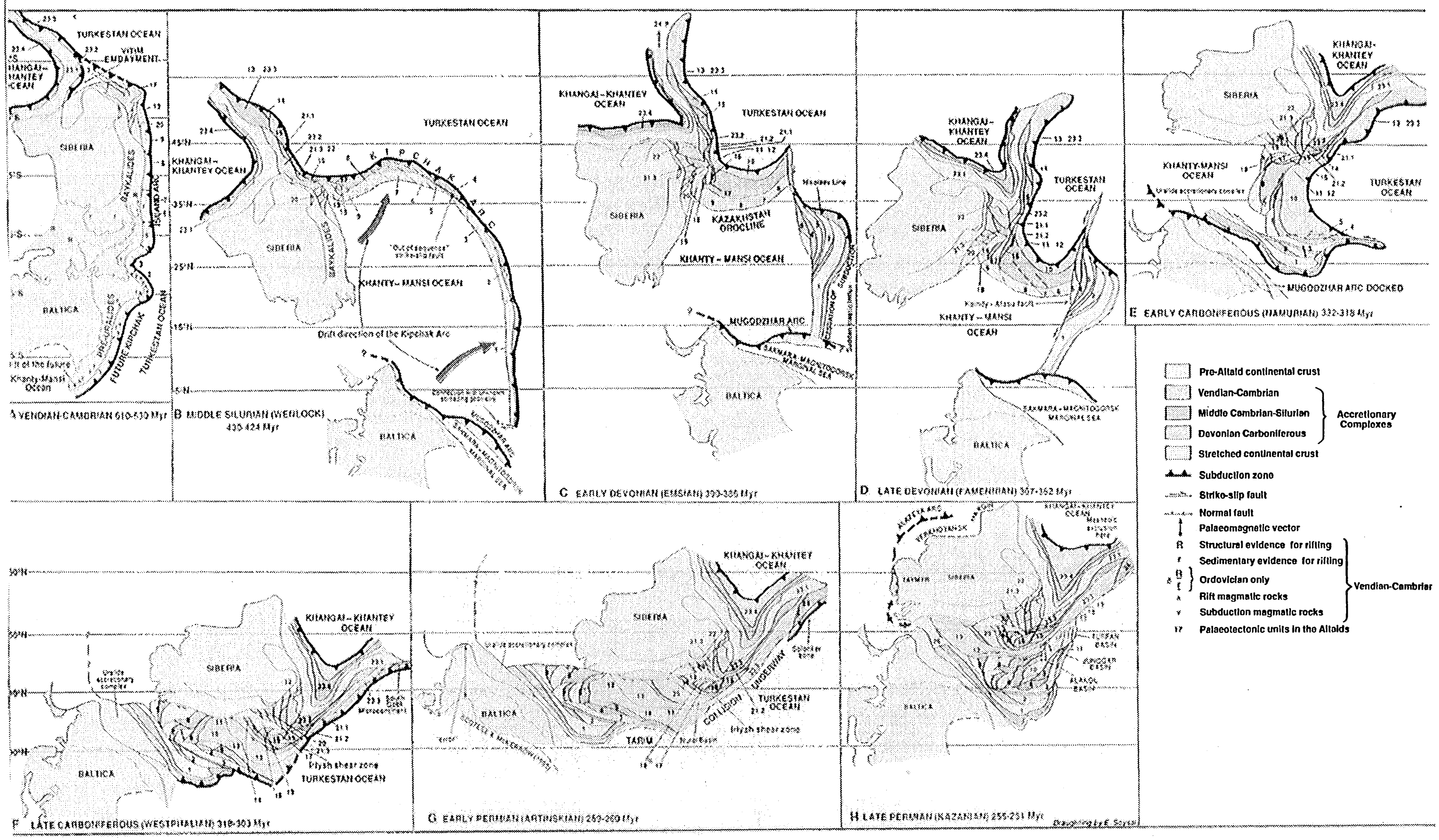
26
0
km
1000

accretionary complex, Šengör and coworkers abandoned the use of ophiolite belts as evolutionary markers and concentrated instead on the identification of magmatic fronts of former arcs as structural markers. Central to their analysis is formation during the Cambrian (Šengör et al.,1994), or late Vendian to Cambro-Ordovician (Šengör et al.,1993), of a gigantic arc complex, the Kipchak Arc, which separated at an early stage from Baltica-Siberia and became subsequently telescoped by a hypothised convergence of Baltica toward the Siberian Craton. Sedimentation in this entire complex now forming the Altaids, progressed from pelagic in the Late Vendian and Cambrian, to Ordovician and Silurian flysch, and finally to starving of the western part of the basin with terrestrial deposits in the Early Devonian. Notably, this is the time that Kazakhstan started to move northward as will be described in part two of this review (Record 1996/52) in the palaeomagnetic analysis section. Accretionary activity continued in other areas but ended by the Early to middle Carboniferous with intense tectonisation, telescoping and cratonisation of the arc complex by northward advance of Baltica as interpreted from Baltic (Torsvik et al.,1992) and Siberian palaeomagnetic data (Šengör et al.,1993: figure 3; Fig.10). Pre-empting discussions in the palaeomagnetic analysis section (Record 1996/52) it should be noted that the newly-determined Carboniferous APWP for the Tamworth Belt allows substitution of Greater Australia for Baltica as the northward converging block, carrying with it the Tarim block which became accreted to the Altaids upon middle to Late Carboniferous reversal of eastern Gondwana's northward movement into a southern direction. With regard to the Early to Middle Palaeozoic equatorial positions of Siberia and Greater Australia, a possible relationship between the Kipchak Arc and arc complexes now incorporated in the Tasmanides - the New England Arc in particular - may be worth investigating. The large-scale movement of Baltica with respect to Siberia during the Carboniferous, assumed by Šengör, may be questioned for the reason that Siberia was already accreted to Laurentia upon Middle Silurian closure of the Iapetus Ocean (Scotese and McKerrow,1990; Scotese and McKerrow,1991).

Figure 9 [previous page] Schematic structural overview of the Altaids showing first-order tectonic units, pre-Altaid continental fragments, Altaid accretionary complexes and Altaid magmatic fronts, after Šengör et al. (1993, fig.2, box 1). The combined magmatic fronts carry only the symbols representing the earliest and latest activity. Along the strike-slip faults only the major Altaid displacements are shown. Legend: 1=Valerianov-Chatkal (Pre-Altaid continental basement, Altaid accretionary complex and magmatic arc), 2=Baykonur-Beshtash (Pre-Altaid continental fragment, Early Palaeozoic accretionary complex and magmatic arc), 3=Chu-Terskey (as above), 4=Sarytum (Pre-Altaid continental basement, Altaid accretionary complex and magmatic arc), 5=Atasu-Mointy (as above), 6=Tengiz (as above), 7=Kaimyk Kol-Kökchetav (as above), 8=Yerementau-Chingiz-Tabagatai, 9=Ishim (Pre-Altaid continental basement, Altaid arc, Altaid accretionary complex), 10=Junggaro-Balkhash (Altaid accretionary complex and arc), 11=Zharma-Saur (Magmatic arc and accretionary complex), 12=Tar-Muromtsev (Magmatic arc and accretionary wedge: displaced fragment of 11), 13=Surgut (Accretionary wedge overlain by volcanic arc), 14=Kolyvan-Rudny Altay (Accretionary wedge and volcanic arc), 15=Gorny Altay (Early Palaeozoic accretionary wedge overlain by Middle Palaeozoic magmatic arc: farther west in the "South Altay" Middle Palaeozoic accretionary wedge with forearc basin), 16= Anuy-Chuya (Arc, accretionary complex and forearc basin), 17=Barnauf (Inferred Precambrian block under Mesozoic-Cenozoic deposits), 18=Salair (Accretionary complex and volcanic arc), 19=Tomsk (Pre-Altaid continental fragment), 20=Satenev (Fragments of the Tomsk unit), 21=Kharkhirin-Western Sayan (Accretionary wedge and volcanic arc), 22=Oka-Jedinsk (Volcanic arc and accretionary complex), 23=Tuva-Mongol sensu lato, 23.1=Tuva Mongol sensu stricto (Vendian-Permian magmatic arc on pre-Altaid continental basement), 23.2=Ozernaya (Tuva-Mongol magmatic arc, migrated onto an accretionary arc complex), 23.3=South Mongolian (Accretionary wedge, grown to the south of the Tuva-Mongol s.s. unit from Ordovician to Early Carboniferous), 23.4=Khangai-Khantey (Accretionary wedge and magmatic arc), 24=South Gobi (Magmatic arc on pre-Altaid continental basement), 25=Nurol (Permo-Mesozoic basin overlying stretched continental crust), 26=Nadim (Permo-Mesozoic basin overlying stretched continental crust).

Fig.10 [opposite page] Schematic overview of Palaeozoic interaction of the Baltic and Siberian cratons and consequent evolution of the Kipchak Arc into the Altaids complex, after Šengör et al. (1993, fig.3).


A VENDIAN-CAMBRIAN 610-530 Myr
B MIDDLE SILURIAN (WENLOCK) 430-424 Myr
C EARLY DEVONIAN (EMSIAN) 393-386 Myr
D LATE DEVONIAN (FAMENNIAN) 367-362 Myr
E EARLY CARBONIFEROUS (NAMURIAN) 332-318 Myr
F LATE CARBONIFEROUS (WESTPHALIAN) 318-303 Myr
G EARLY PERMIAN (ARTINSKIAN) 280-269 Myr
H LATE PERMIAN (KAZANIAN) 255-251 Myr
TURKESTAN OCEAN
KHANGAI-KHANTEY OCEAN
KHANTY-MANSI OCEAN
SIBERIA
BALTICA
KIPCHAK ARC
BAYKALIDES
MUGODZHAR ARC
KAZAKHSTAN OROCLINE
Drift direction of the Kipchak Arc
MUGODZHAR ARC DOCKED
Irtysh shear zone
TARIM
Pro-Altaid continental crust
Vendian-Cambrian
Middle Cambrian-Silurian
Devonian Carboniferous
Stretched continental crust
Accretionary Complexes
Subduction zone
Strike-slip fault
Normal fault
Palaeomagnetic vector
Structural evidence for rifting
Sedimentary evidence for rifting
Ordovician only
Rift magmatic rocks
Subduction magmatic rocks
Vendian-Cambrian
Palaeotectonic units in the Altaids

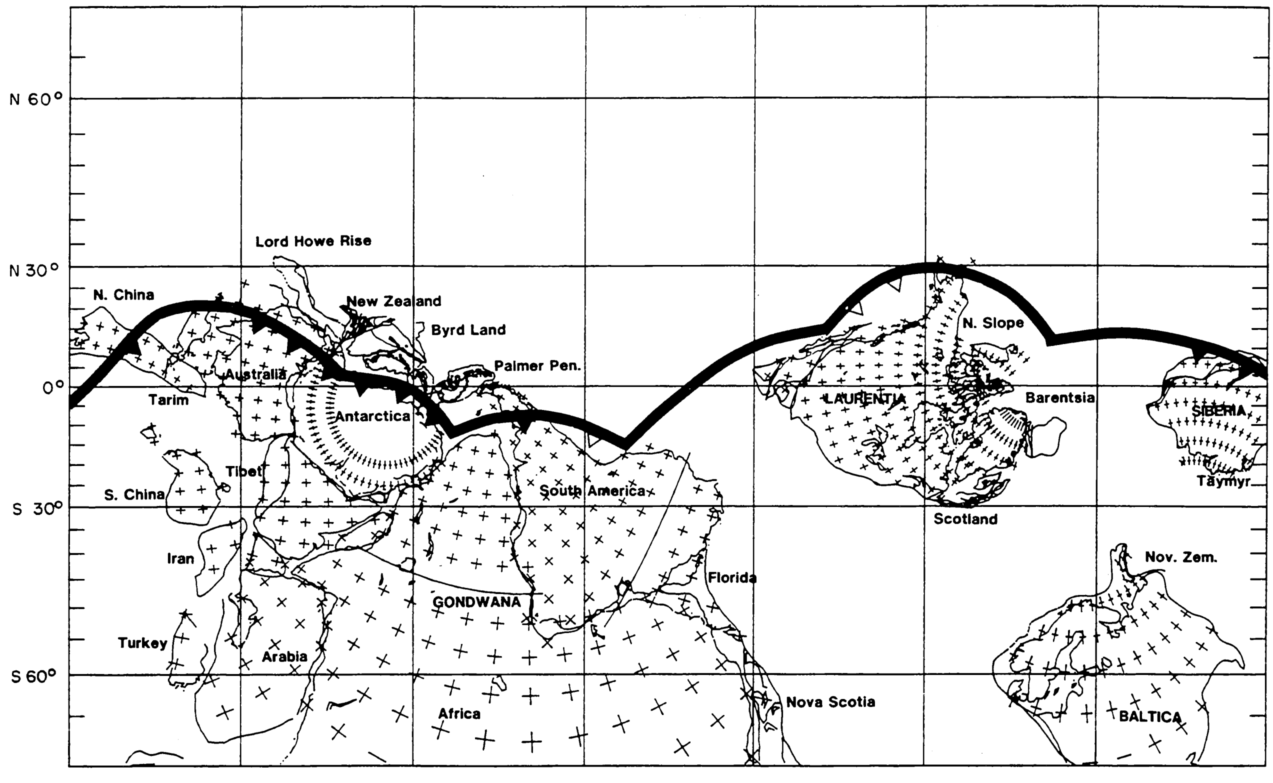


Figure 11 Late Cambrian reconstruction, after Scotese (1987, fig.1), showing the Panthallassic Ocean occupying much of the northern hemisphere. Thick black line represents the position of a subduction zone evidenced by subduction related volcanics and plutonism (solid triangles) and probable island arc volcanism (open triangles) of Early and Middle Palaeozoic age. Areas outside the subduction zone boundary represent terranes accreted after the Early Palaeozoic. Present-day geographic areas are labelled. Lines of latitude spaced at 30°intervals.

"Chicago Group": Scotese, Rowley, Nie Shangyou, Ziegler

Scotese is, perhaps, the most widely cited participant in numerous successive palaeogeographic reconstruction projects, such as the Palaeogeographic Atlas Project at the University of Chicago, the Palaeoceanographic Mapping Project (POMP) of the University of Texas, and the PALEOMAP Project of the International Lithosphere Program. He has demonstrated in a remarkable series of Phanerozoic palaeogeographic world maps (Ziegler et al.,1977,1979; Scotese et al.,1979; Scotese,1984; Scotese et al.,1985; Scotese,1987; Lawver and Scotese,1987; Scotese and Barrett,1990; Scotese and McKerrow,1990,1991; Golonka et al.,1994; Scotese and Langford,1995), developed over more than 15 years with the use of sophisticated reconstruction software, an evolving insight into the Phanerozoic movements of continental fragments through dispersion of Gondwana and accretion to Laurasia. These reconstructions are based on (i) the global palaeomagnetic data record foremost, (ii) a geologic database with control on age and distribution of subduction and rifting events, (iii) a comprehensive biogeographic database, (iv) a database with climatologically sensitive lithofacies indicators, and (v) predictive plate motion modelling based on understanding of driving forces. These reconstructions have been used widely as base maps for the study of former global patterns of biostratigraphy, lithofacies etc.

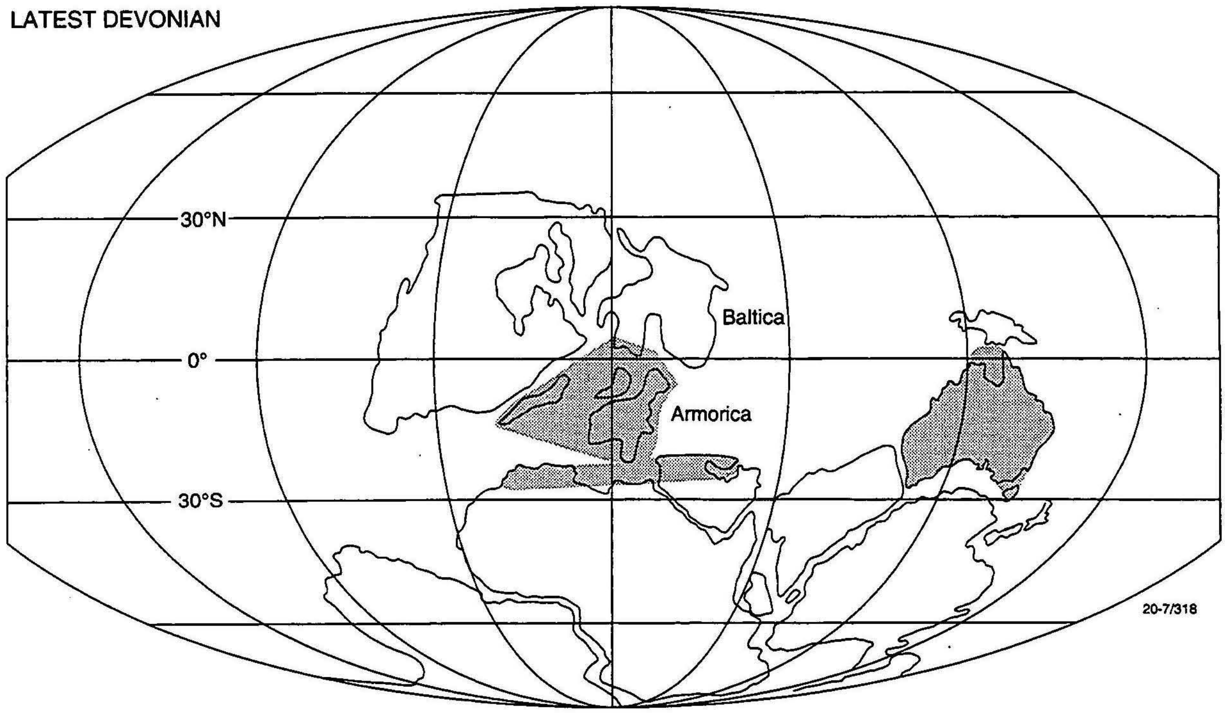


Figure 12 Latest Devonian reconstruction of Gondwana and Laurentia based on palaeomagnetic results from the basal Mount Eclipse Sandstone of the Ngalia Basin (Klootwijk et al.,1993).

Scotese's Early Palaeozoic reconstructions show a combined Tarim-North China block located with North China to the north of, and the Tarim block adjacent to the Birds Head of Irian Jaya. Such placement is consistent with the interpretation that the Chilian (Qilian)-Shan mobile belt of the North China block may be a continuation of the Trans-Antarctic - Tasman subduction zone. South China is reconstructed outboard of the Lhasa block, itself adjacent to the northern Indian margin, and the Lut block and Central Afghanistan are placed opposite northwestern India and northeastern Arabia (Fig.11). Scotese (1987) struggled in particular with the Late Devonian reconstruction of Gondwana versus Laurasia. For this particular period, three independent lines of constraining evidence appear to be contradictory, i.e. palaeomagnetism, biogeographic affinities, and distribution of climatically sensitive lithofacies. His preference is for an equatorial latitude of northern Gondwana as indicated by climatologically sensitive lithofacies. This reconstruction contradicted the then available palaeomagnetic data, but is in good agreement with new data from the Late Devonian to Early Carboniferous Mount Eclipse Sandstone of the Ngalia Basin (Fig.12; e.g. Klootwijk et al.,1993).

Scotese and McKerrow (1990), detail in their seminal paper for the Symposium on Palaeozoic Biogeography and Palaeogeography, a series of global reconstruction maps for the Palaeozoic that have been used extensively as base maps for biogeographic analyses. These base maps are still highly relevant in the context of this review, even though some plate motions have been updated since then and interpretative subduction and accretion processes have been added to the reconstructions (Klein

TABLE 1
Rotation parameters used to assemble Laurentia and Gondwana, after Scotese and McKerrow (1990: table 1)

Plate	Latitude	Longitude	Angle	Reference Plate
Laurentia				
Florida	62.20	-15.90	78.80	Africa
Greenland	-50.07	26.29	7.74	Laurentia
North Alaska	70.11	-128.16	-78.00	Laurentia
Mexico	-48.60	94.10	13.00	Laurentia
Baja California	-46.48	-76.52	7.48	Mexico
Chortis	-39.70	87.90	31.10	Mexico
North Scotland	-82.30	-25.90	33.50	Laurentia
Gondwana				
Arabia	26.50	21.50	-7.60	Africa
Madagascar	-1.70	-87.80	22.20	Africa
South America	45.50	-32.20	58.20	Africa
Yucatan	-2.92	97.80	74.50	S. America
India	-22.38	-157.10	55.91	Madagascar
Ceylon	-11.12	-99.73	28.67	India
Variscan Europe	41.85	36.60	13.67	Africa
Iberia	-45.73	-178.30	37.10	Europe
Apulia	21.80	116.80	2.20	Europe
Australia	-1.58	39.02	-31.29	E. Antarctica
East Antarctica	5.46	-162.90	-92.60	India
Marie Byrdland	62.27	21.84	13.27	E. Antarctica
West Antarctica	-64.24	-75.64	91.09	S. America
Ellsworth	-63.81	-79.40	87.02	S. America
North New Zealand	24.19	-19.91	44.61	Australia
South New Zealand	65.14	-52.00	62.38	Marie Byrdland
Chatham Rise	41.00	-15.90	7.47	S. New Zealand
Cimmerian Terranes				
Shan Thai	5.98	114.75	138.37	Australia
Tibet	-29.90	-84.49	111.20	Shan Thai
Iran	52.37	32.75	32.38	Tibet
Turkey	-17.72	-135.8	11.19	Iran
Cathaysian terranes				
South China	2.17	161.40	39.30	Australia
North China	-37.80	-51.10	40.40	S. China
Indochina	9.40	93.80	41.40	S. China

et al.,1994; Golonka et al.,1994 - A current version of this set of Phanerozoic palaeogeographic maps is available upon request from Jan Golonka (Mobil Exploration and Producing Technical Centre, Dallas, TX 75265-0232, USA). The base maps show several important new features: (i) plate motions for the Gondwanan continents are not based on direct palaeomagnetic data, but instead on an alternative APWP derived from palaeoclimatically restricted lithofacies data (Scotese and Barrett,1990); (ii) the Devonian reconstructions show near-contact between Laurentia (North America) and northwestern Gondwana rather than a wide ocean; (iii) a new scenario is presented for the motions of the Cathaysian continents (South China, North China, Indochina) although no factual arguments are advanced for the postulated Early to Middle Devonian separation from Gondwana, other than relating this to a new phase of plate motions initiated after Late Silurian closure of the Iapetus Ocean; (iv) Kazakhstan is shown as a western extension of Siberia, but this approach is abandoned in subsequent reconstruction models

TABLE 2

Rotation parameters used to assemble Laurentia and Gondwana, after Scotese and McKerrow (1991: table 1)

A: Gondwana (rotations with respect to fixed Africa)

Continental Block	Latitude	Longitude	Angle
Central Gondwana			
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
Northwest Margin			
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
West Avalonia	61.68	-4.03	71.23
East Avalonia	25.60	16.60	39.42
Turkey	-46.50	174.0	7.70
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
SE and SW Margin			
North New Zealand	4.83	-54.80	84.68
South New Zealand	29.93	-58.89	103.9
Marie Byrdland	3.19	-33.40	61.47
W. Antarctica Peninsula	-36.90	-19.92	81.40

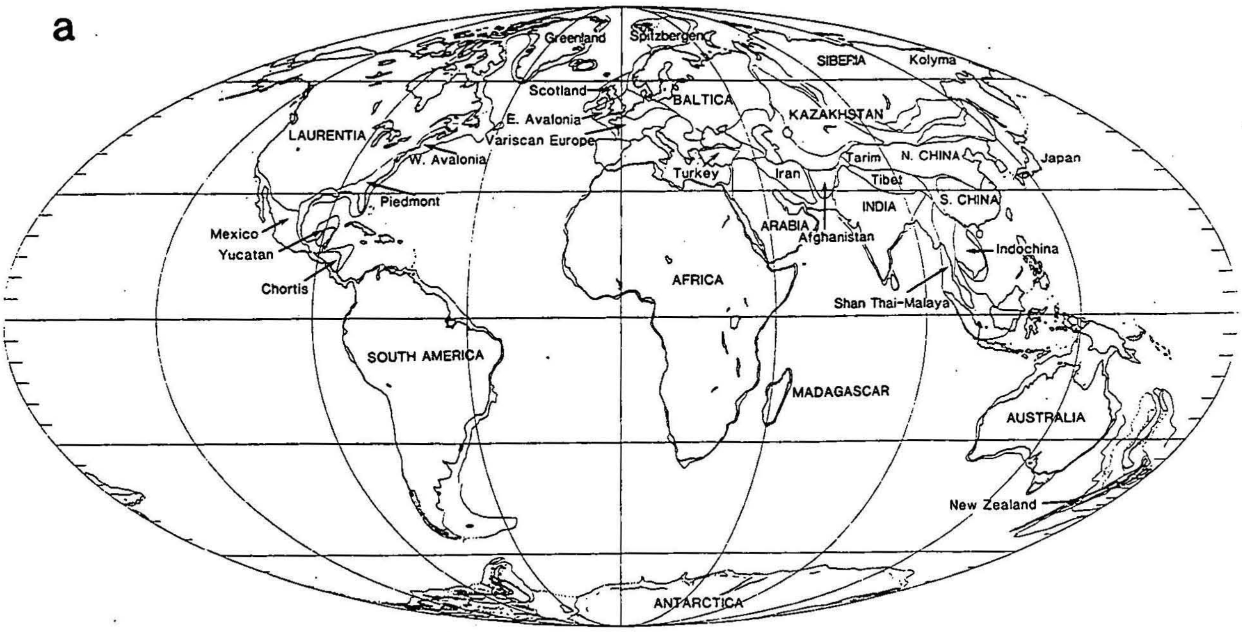
B: Gondwana (rotations with respect to fixed Africa)

Continental Block	Latitude	Longitude	Angle
Greenland	-50.07	26.29	7.74
Alaska North 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
North Scotland	-82.30	-25.90	33.50
Barentsia (Svalbard)	-81.45	110.7	50.10

(Golonka et al.,1994); (v) the position of Siberia (and Kazakhstan) from palaeomagnetic results of Khramov and Rodionov (1980) and Khramov et al. (1981) is adapted to satisfy biostratigraphic indications for lower northern latitudes; (vi) a list of reconstruction parameters is reproduced in Table 1, with a slightly updated version (Scotese and McKerrow,1991) reproduced in Table 2.

Some of the more relevant base maps of Scotese and McKerrow (1990) for the Palaeozoic are

a



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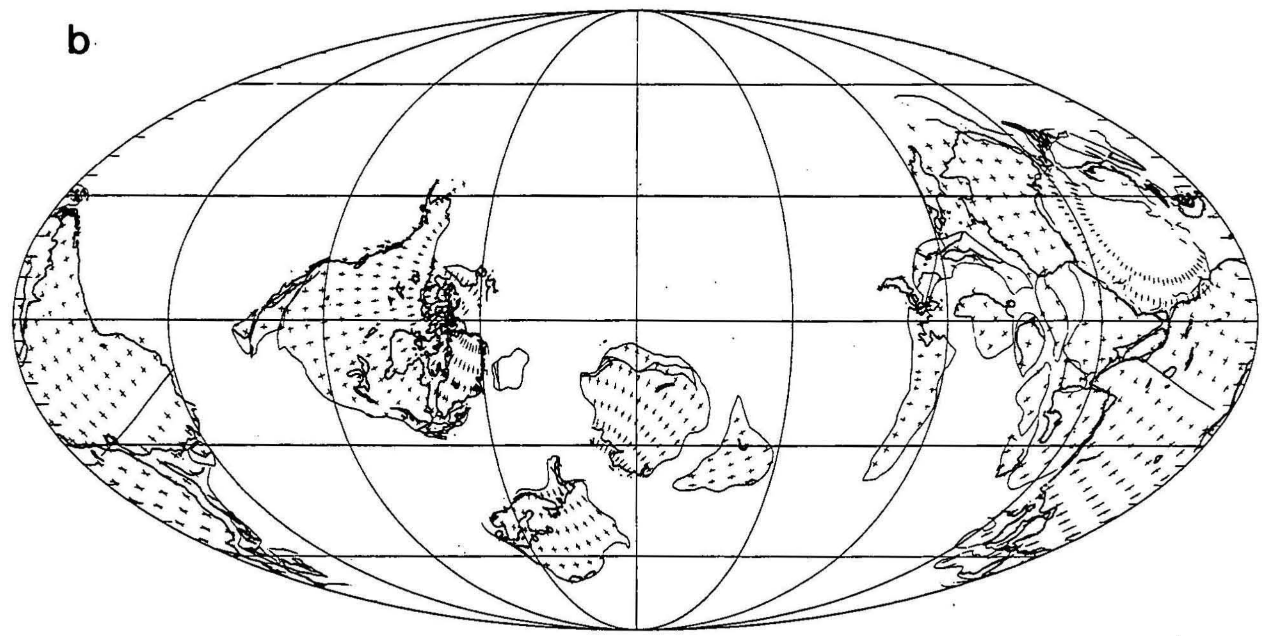
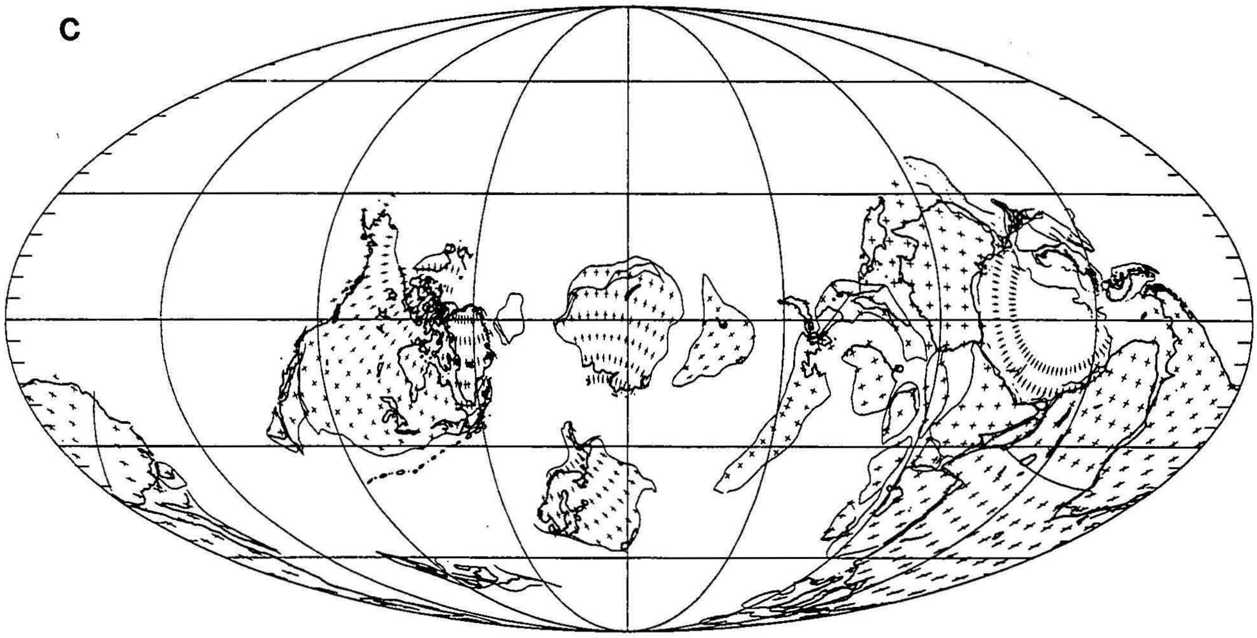


Early Cambrian

Figure 13 [above and following pages] Palaeozoic reconstructions after Scotese and McKerrow (1990). A: Present-day sutures of Palaeozoic continents (ibid.,fig.1). B: Early Cambrian reconstruction (ibid.,fig.3). C: Early Ordovician reconstruction (ibid.,fig.7). D: Latest Ordovician reconstruction (ibid.,fig.9). E: Late Silurian reconstruction (ibid.,fig.12). F: Early Devonian reconstruction (ibid.,fig.13). G: Late Devonian (Famennian) reconstruction (ibid.,fig.16). H: Early Carboniferous (Visean) reconstruction (ibid.,fig.17). I: Early Permian (Artinskian) reconstruction (ibid.,fig.20). J: Late Permian (Kazanian) reconstruction (ibid.,fig.21).

c



Early Ordovician (Arenig)

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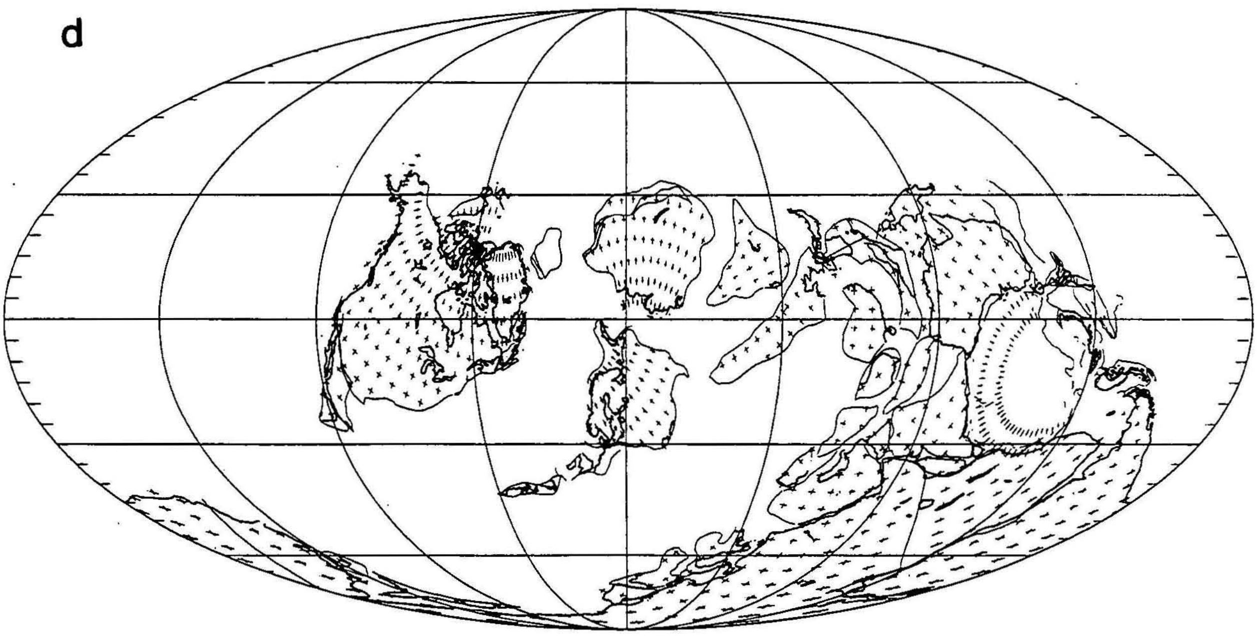
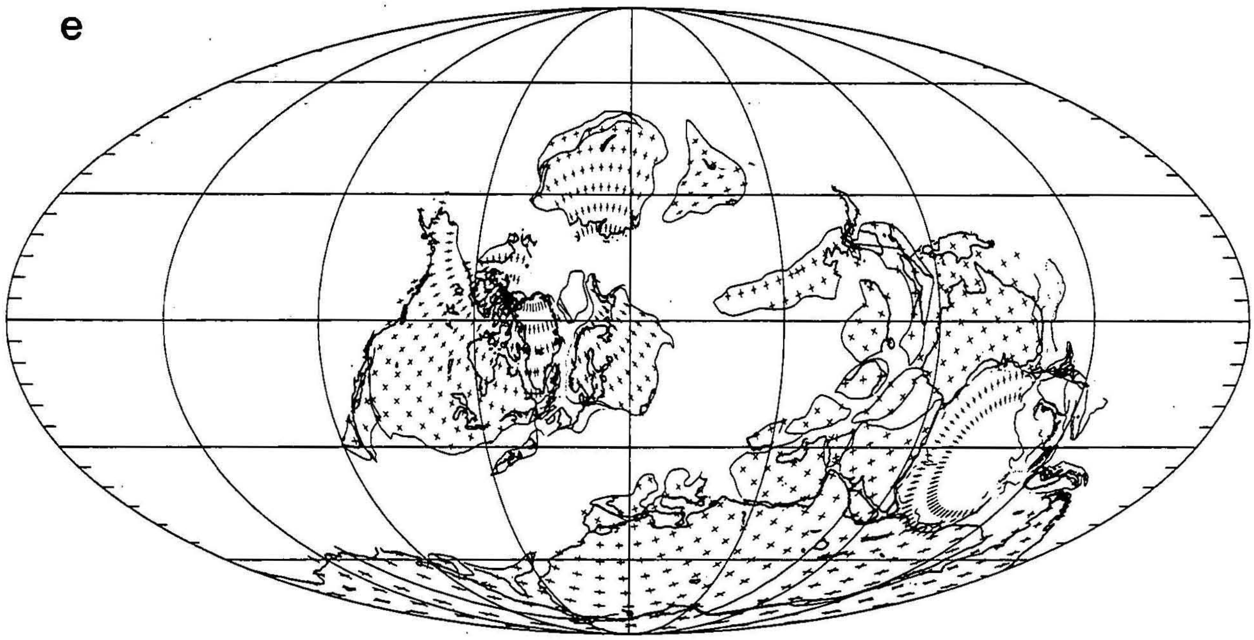


Latest Ordovician (Ashgill)

reproduced herein (Fig.13A-J), as well as a more recent set of reconstructions for the Late Carboniferous to Late Jurassic (Scotese, in Klein et al.,1994) with updated plate motions and, unfortunately unspecified, lithostratigraphic detail (Fig.14A-H). Several of Scotese and McKerrow's remarks regarding Asian continental blocks of eastern Gondwana origin are worth highlighting:

e



Late Silurian (Ludlow)

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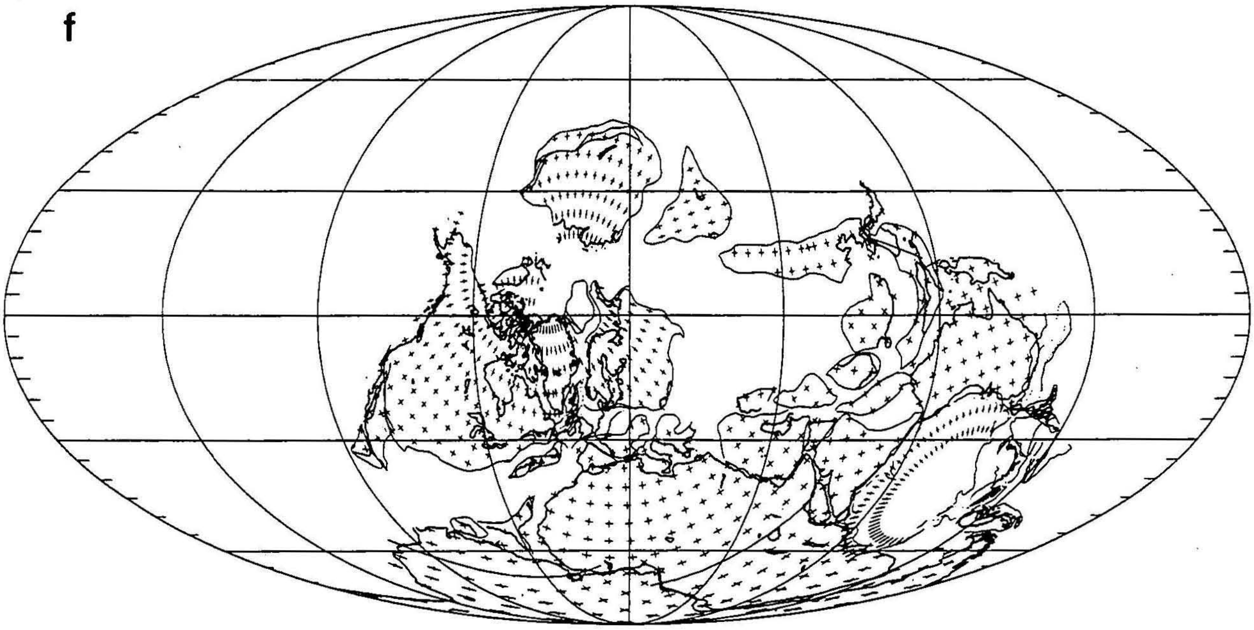
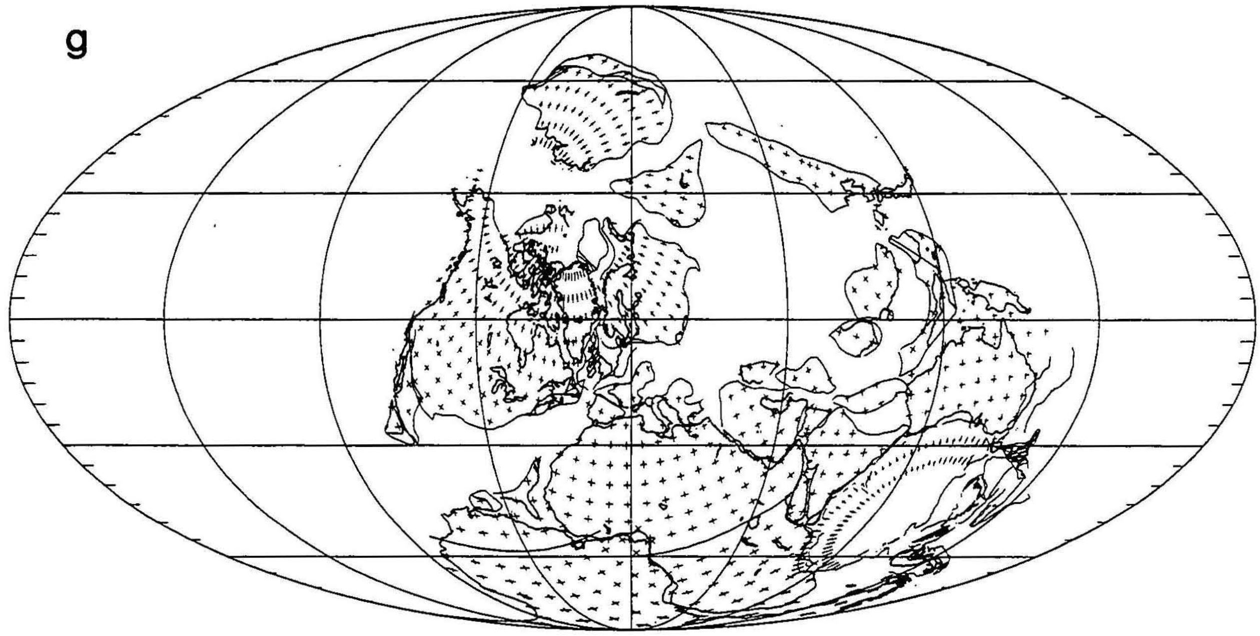


Early Devonian (Gedinnian)

- Siberia (and Kazakhstan) moved northward from the Cambrian to the Early Carboniferous, rotated clockwise during the mid-Carboniferous and collided with Baltica along the Ural Mountains-Irtysch Crush Zone in the Late Carboniferous-Early Permian;
- Tarim and North China are regarded as separated along the Qilian Shan but are shown united for simplicity. Tarim

g



Late Devonian (Famennian)

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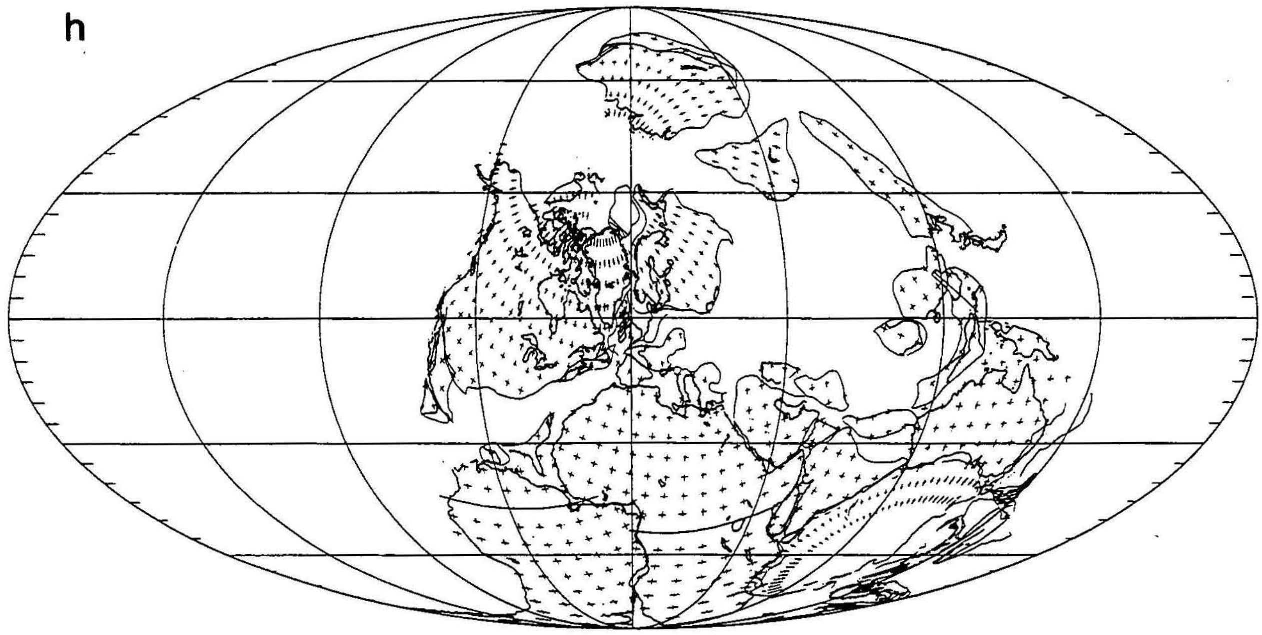
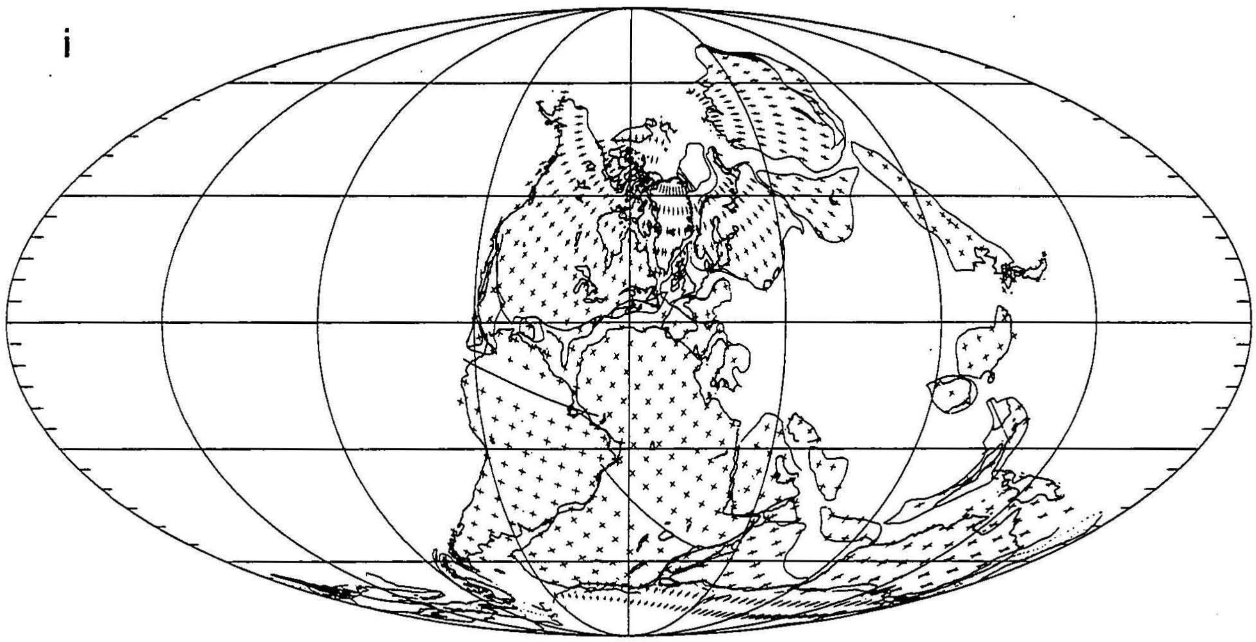


Early Carboniferous (Visean)

appears to have collided with Siberia and Kazakhstan during the Late Carboniferous-Early Permian, whereas North China and South China did not join Laurasia until the Late Triassic-Early Jurassic Indosinian Orogeny;
South China is reconstructed outboard of northwestern Australia and the reconstructed Qiangtang - Shan-Thai blocks, and near to Greater India, but uncertainty in Palaeozoic palaeomagnetic polarity interpretation leaves it open to

i



Early Permian (Artinskian)

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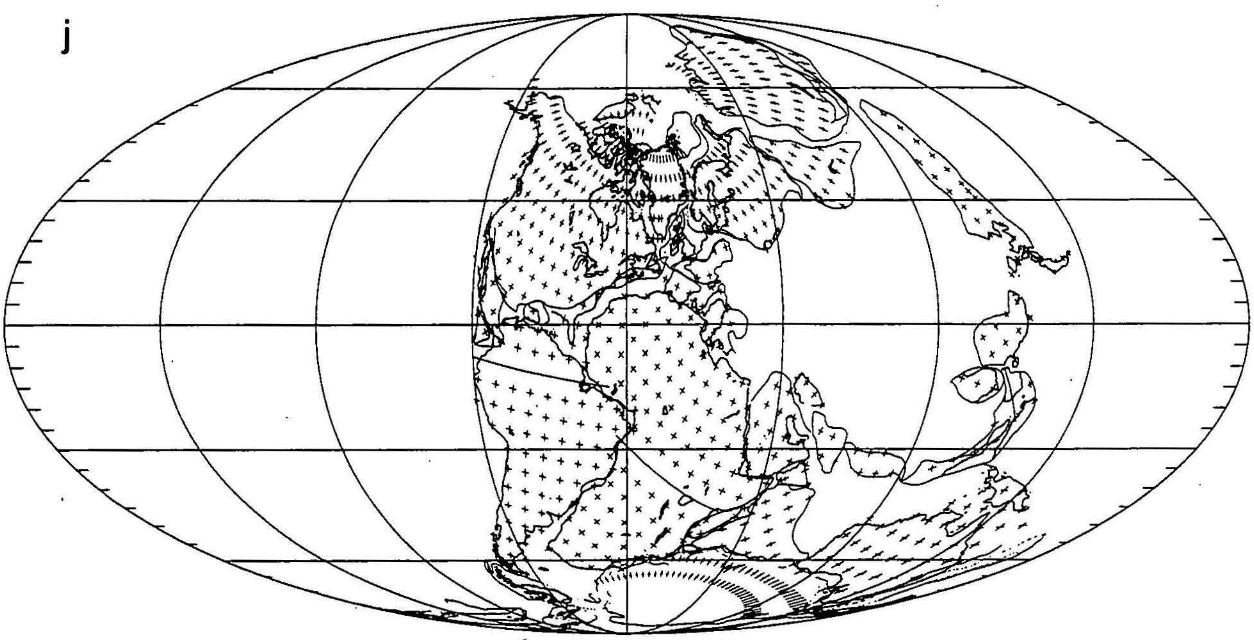


Late Permian (Kazanian)

question whether South China faced eastern Gondwana with its northwestern or southeastern margin;
The location of North China and Tarim is uncertain palaeomagnetically. North China is relocated to the northwest of New Guinea with possible attachment to South China through Korea. Such a reconstruction relocates the Cathaysian continents essentially in an arc off East Gondwana, stretching between South Mongolia and the East Australian Arc;

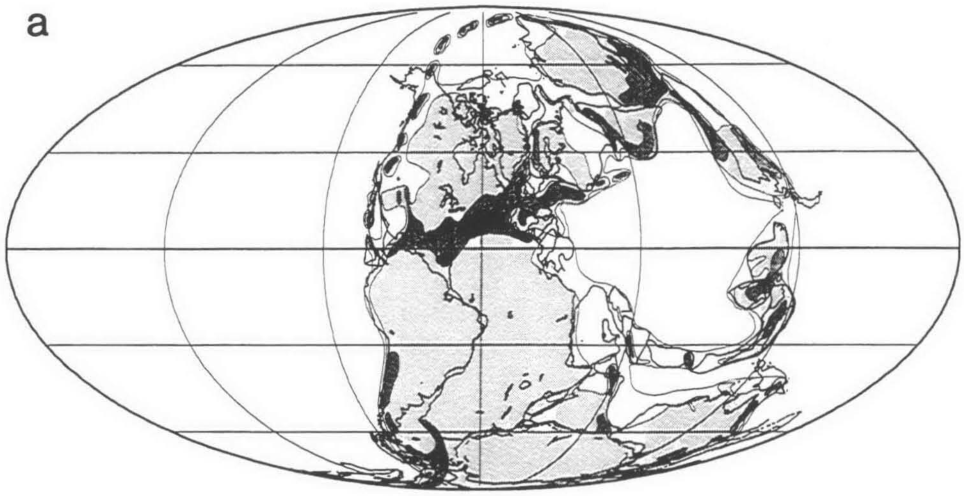
- The main Cimmerian continents Turkey, Iran, Tibet (Qiantang and Lhasa), Burma-Malaya (Shan-Thai-Malaya, Shan-Thai or Sibumasu) and Indochina are relocated outboard of northern Gondwana from Arabia to northwestern Australia;
- Cimmeria started to rift in the Late Palaeozoic, crossed the Palaeo-Tethys, and collided with southern Laurasia during the Middle to Late Triassic Cimmerian Orogeny;
- Western Pangea amalgamated during the Carboniferous and Early Permian with closure of several oceans - the Rheic Ocean between northern Europe and Gondwana, the Phoibic Ocean between Laurentia and Gondwana, and the Pleionic Ocean between Baltica and Siberia-Kazakhstan. This change in continental configuration and continentality is implicitely linked with a major global cooling event in the late Namurian. It should be stressed though that the start of the "Kiaman" (Permo-Carboniferous Reverse Superchron) is now likewise dated as late Namurian (e.g. Klootwijk et al.,1994) and the two events may be causally related;
- The configuration of the blocks that eventually formed the eastern half of Pangea is still problematic and is treated less simplistically elsewhere (e.g. Nie et al.,1990). Five terranes are shown as separate blocks (Fig.13): South China, Indochina, Burma-Malaya, Iran and Afghanistan (Helmand block). Five others have been combined into composite blocks: Tarim and Sino-Korea are shown as North China and the West Qiangtang, East Qiangtang and Lhasa blocks are combined into a Tibetan block. The terranes of Manchuria, originally located along the southern margin of Siberia (Nie et al.,1990) are not shown at all.

Scotese and McKerrow's (1991) paper on Ordovician plate tectonic reconstructions updates Scotese's (1987) concept of a global Panthalassic subduction complex and also updates Scotese and McKerrow's (1990) global reconstructions, particularly for the eastern Asian fragments of Gondwanan origin (Fig.15, reconstruction parameters detailed in Table 2). Scotese extends Šengör's (1984,1985) Early Carboniferous to Early Cretaceous Palaeo-Tethys concept and defines the Paleo-Tethys in the sense of Ziegler's (1988) Proto-Tethys, which existed throughout the Palaeozoic.

The location and orientation of several Gondwanan fragments on both the Paleo-Tethys-facing and Panthalassa-facing sides of Gondwana differ from the Scotese and McKerrow (1990) reconstructions. The Lut-Helmand, Qiangtang, Lhasa and Indochina blocks have maintained their positions with respect to Greater India, but the South China and Burma-Malaya blocks have swapped positions, apparently following Burrett et al. (1990). Thus South China is rotated 180 degrees so that its present-day eastern margin faces northwest and its western margin faces northwestern India and Pakistan. The Burma-Malaya block is located opposite the northwestern margin of Australia-Irian Jaya. The palaeoposition of the Tarim block is regarded as somewhat uncertain and is not shown on Figure 15. It is described, however, as adjacent to Indochina and South China, rather than adjacent to North China as depicted earlier (Scotese and McKerrow,1990), and outboard of the Qiangtang and Burma-Malaya blocks. The North China block without the Tarim block is rotated 180 degrees and is located directly opposite the New Guinean margin of Australia such that the Qinling-Qilian Shan subduction complex is aligned with the New England segment of the Tasman-Trans Antarctic subduction complex. Kazakhstan is still shown as a southwestern extension of Siberia, but this concept has been abandoned in Golonka et al. (1994).

An important consequence of this Panthalassic subduction concept is the alignment of the Altai-Sayan - Mongol-Okhotsk - Qinling-Qilian Shan subduction zone complexes of central Asia with the Tasman-Trans Antarctic subduction zones of eastern Gondwana. This aspect was not addressed in Šengör et al.'s (1993) paper on the evolution of his central Asian subduction complex (Kipchak Arc, see above), but it provides support for several conclusions derived from the newly determined APWP for New England and detailed in the palaeomagnetic analysis section in part two of this review (Record 1996/52). It is argued there that Greater Australia was involved in Variscan tectonics of the Altaids periphery of the Siberian Craton and this implies that the evolution of the Kipchak Arc may be related to the evolution of the Tasmanides.

a



Late Carboniferous (Westphalian)

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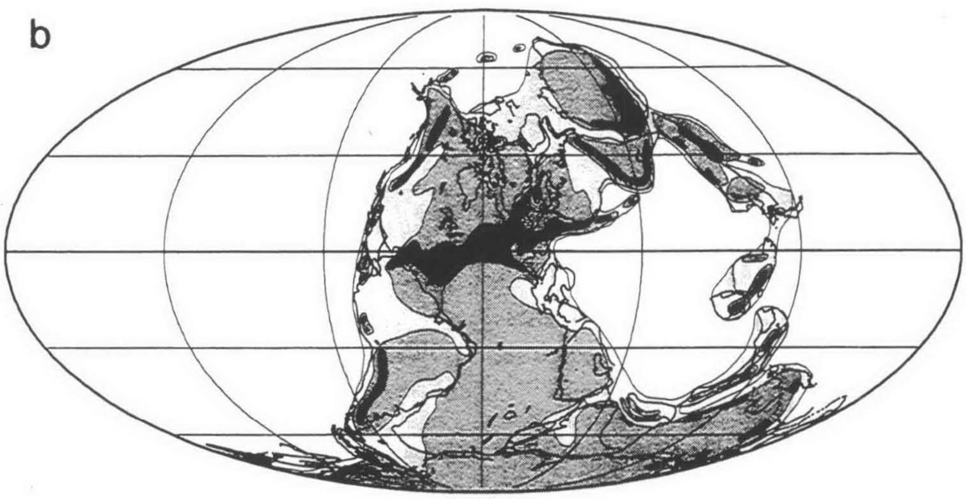
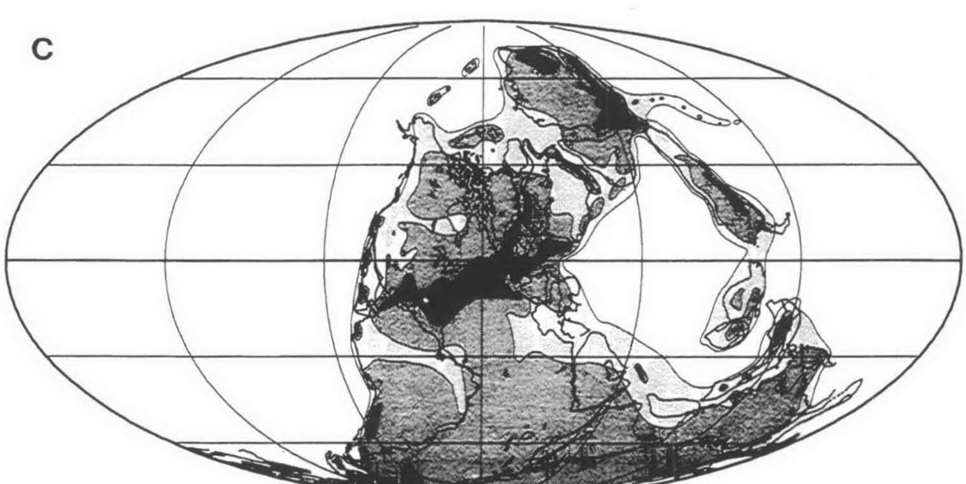


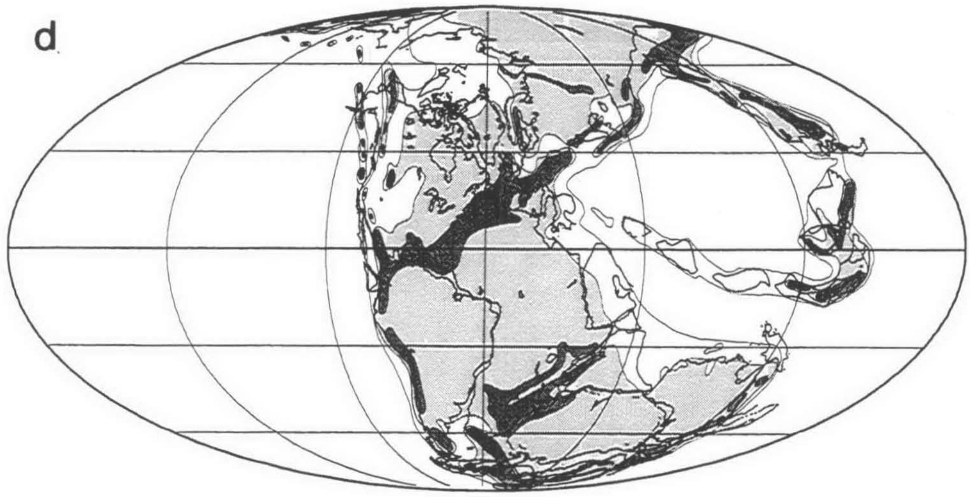
Early Permian (Artinskian)

c



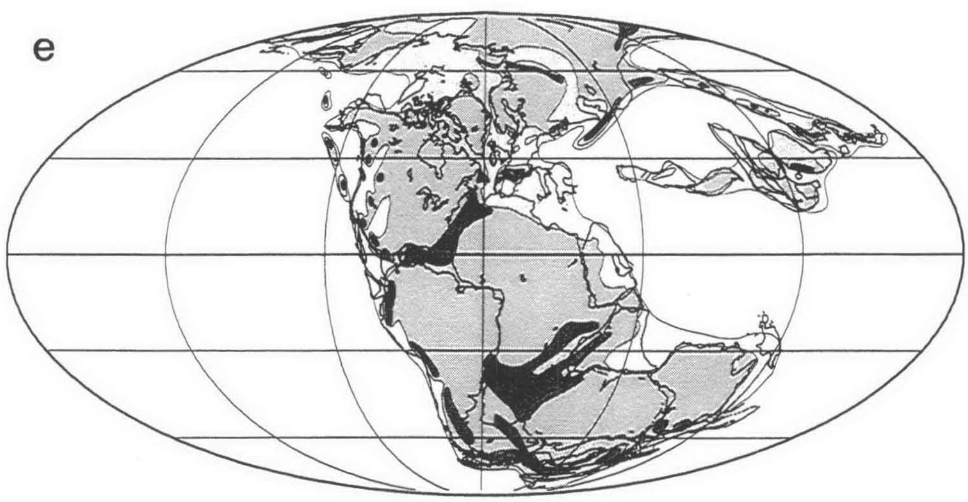
Late Permian (Kazanian)

d



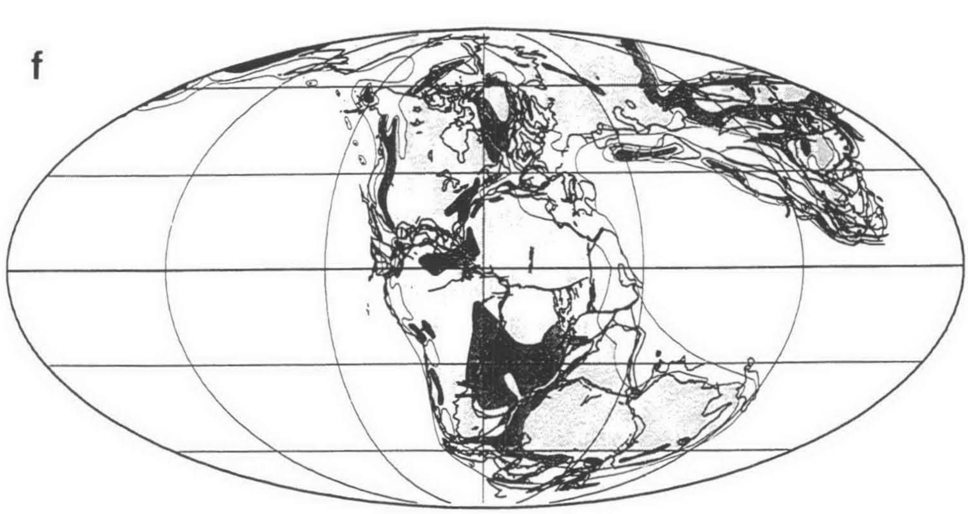
Early Triassic (Induan)

e



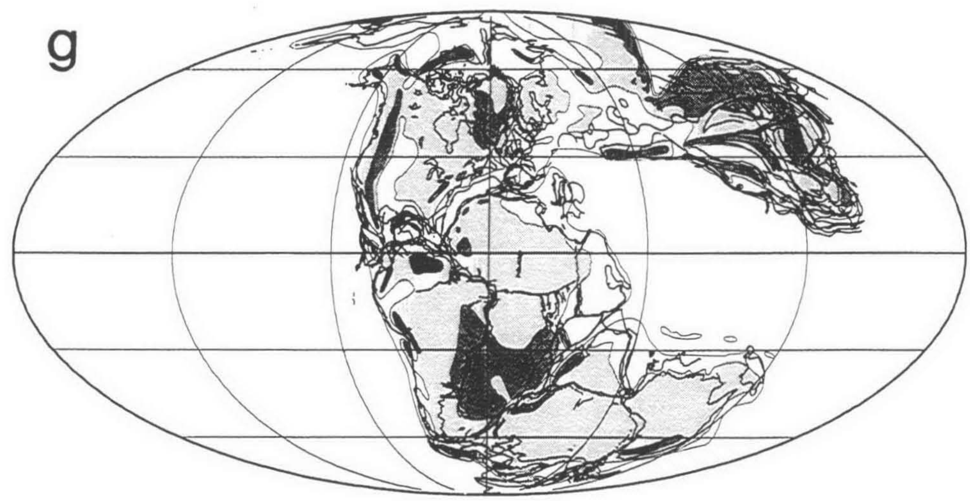
Late Triassic (Norian)

f



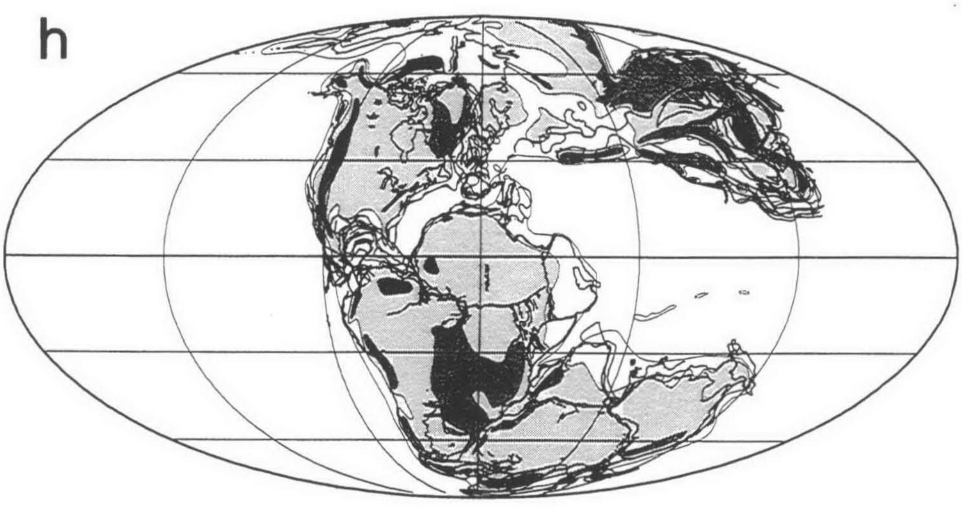
Early Jurassic (Pliensbachian)

g



Middle Jurassic (Callovian)

h



Late Jurassic (Tithonian)

Figure 14 [above and previous pages] Late Carboniferous to Late Jurassic reconstructions after Scotese in Klein et al. (1994). A: Palaeogeographic reconstruction for the Late Carboniferous (Westphalian) (ibid.,fig.1), B: As above for the Early Permian (Artinskian) (ibid.,fig.2); C: As above for the Late Permian (Kazanian) (ibid.,fig.3). D: As above for the Early Triassic (Induan) (ibid.,fig.4); E: As above for the Late Triassic (Norian) (ibid.,fig.5); F: As above for the Early Jurassic (Pliensbachian) (ibid.,fig.6); G: As above for the Middle Jurassic (Callovian) (ibid.,fig.7); H: As above for the Late Jurassic (Tithonian) (ibid.,fig.8).

Rowley et al.'s (1985) paper on Carboniferous reconstructions adds little to the information mentioned above, apart from an observation on evolution of phytogeographic relationships between China and northern Gondwana. Comparison of Early Devonian macro-floras and Tournaisian-early Visean macro- and pollen-floras (Van der Zwan,1981) of China and northern Gondwana indicates a former position

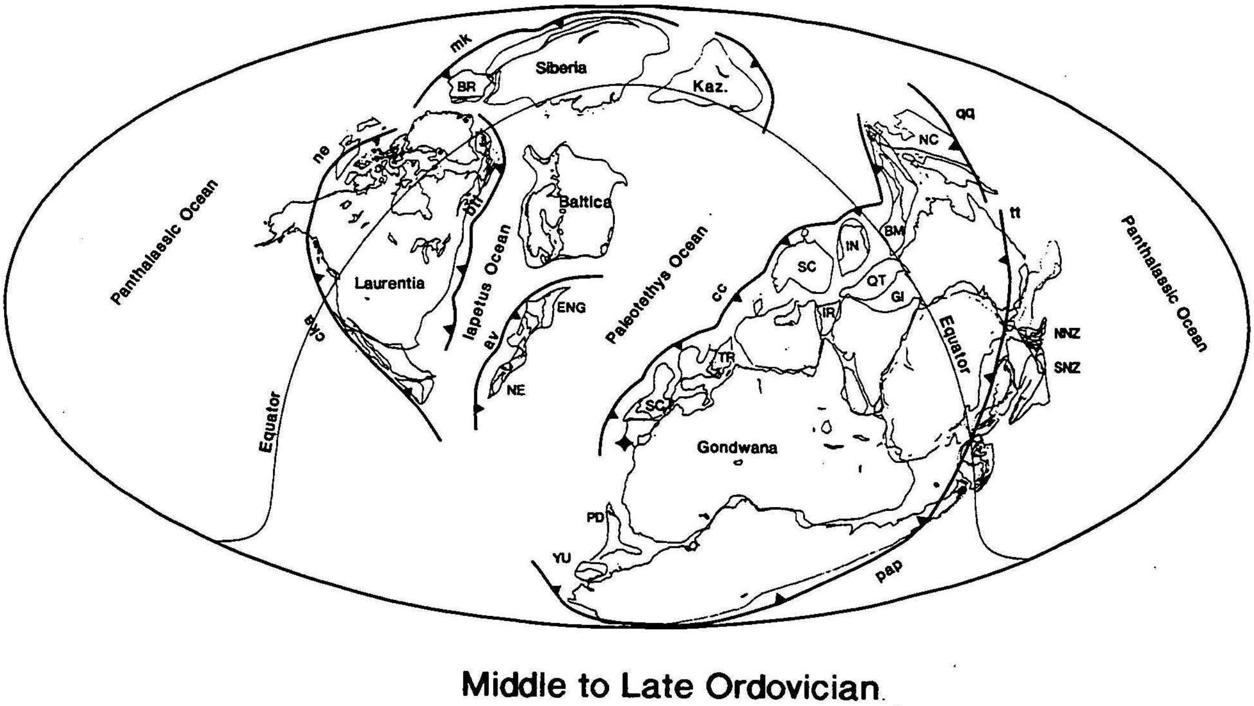


Figure 15 Middle-Late Ordovician reconstruction, after Scotese and McKerrow (1991, fig.1). The southpole is indicated by the diamond symbol near Spain. Legend: BR=Barentsia (Svalbard), ENG=England and Wales, NE=New England and Maritime Canada, YU=Yucatan, PD=Florida and Piedmont of southeastern USA, SCE=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, 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-Petija subduction zone.

along the northern margin of Gondwana, whereas post-Visean floras of China are distinct from Gondwana. This infers separation to have commenced in the late Visean-Early Namurian. It is not clear whether Rowley et al.'s "China" refers to North China, South China, Indochina, or solely to South China as specified in the abstract.

Nie Shangyou provides some interesting palaeoclimatic, floral, lithofacies and biogeographic constraints on the original location, adherence to provinces, and the evolution of northward movements of Cathaysian and Cimmerian fragments (Nie Shangyou et al.,1990; Nie Shangyou,1991). An overview of identified continental blocks and sutures zones (Nie Shangyou et al., fig.1) is reproduced as a useful guide in Figure 16. Nie includes the (originally Cimmerian) Helmand and Western Qiangtang blocks from the Late Permian onwards with the major Cathaysian continents of Yangtze (South China undivided), Indochina, Eastern Qiangtang, Sino-Korea (North China) and Tarim, and includes the Lut block, parts

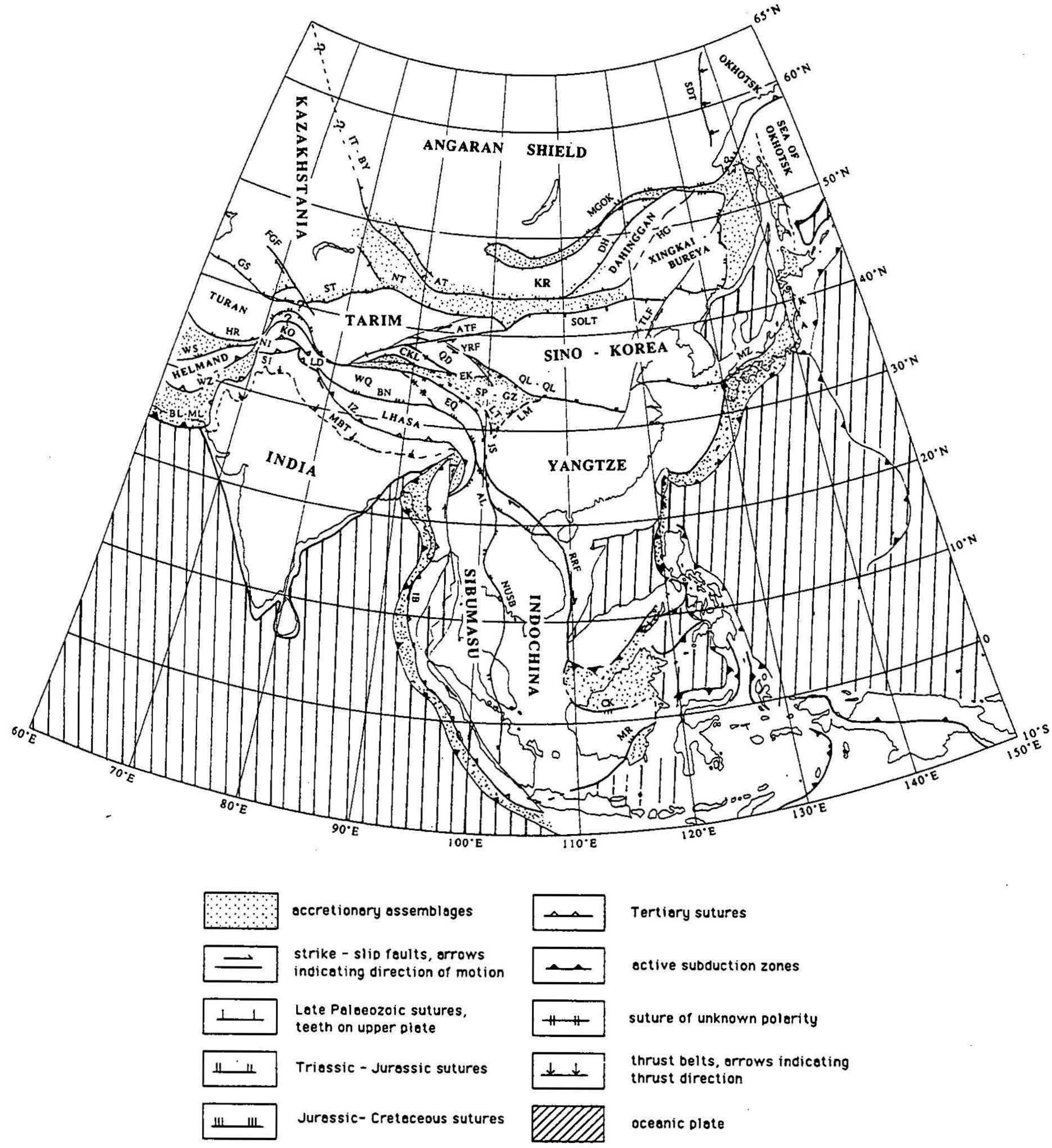


Figure 16 Tectonic subdivisions and sutures for the eastern Asian blocks, after Nie Shangyou. (1991, fig.1). Legend of selected structures: Microcontinents; CKL=Central Kun Lun, EQ=Eastern Qiangtang, KO=Kohistan, QD=Qaidam, WQ=Western Qiangtang, Sutures: AL=Ailaoshan, AT=Altai, BN=Banggong Co-Nujiang, EK=East Kunlun, GS=Ghissar, LD=Ladakh, LM=Longmenshan, MGOK=Mongolo-Okhotsk, NI=North Indus, NT=North Tianshan, NUSB=Nan-Uttaradit-Sra-Kaeo-Bentong, QL-QL=Qilian-Qinling, SI=South Indus, ST=South Tienshan, WS=Waser, WZ=Waziristan, major strike-slip faults: ATF=Altyn Tagh, FGF=Ferghana, RRF=Red River, TLF=Tan-Lu, YRF=Yellow River, Thrust belts: MBT=Main Boundary Thrust, Accretionary Complex; SP-GZ=Songpan-Ganzi.

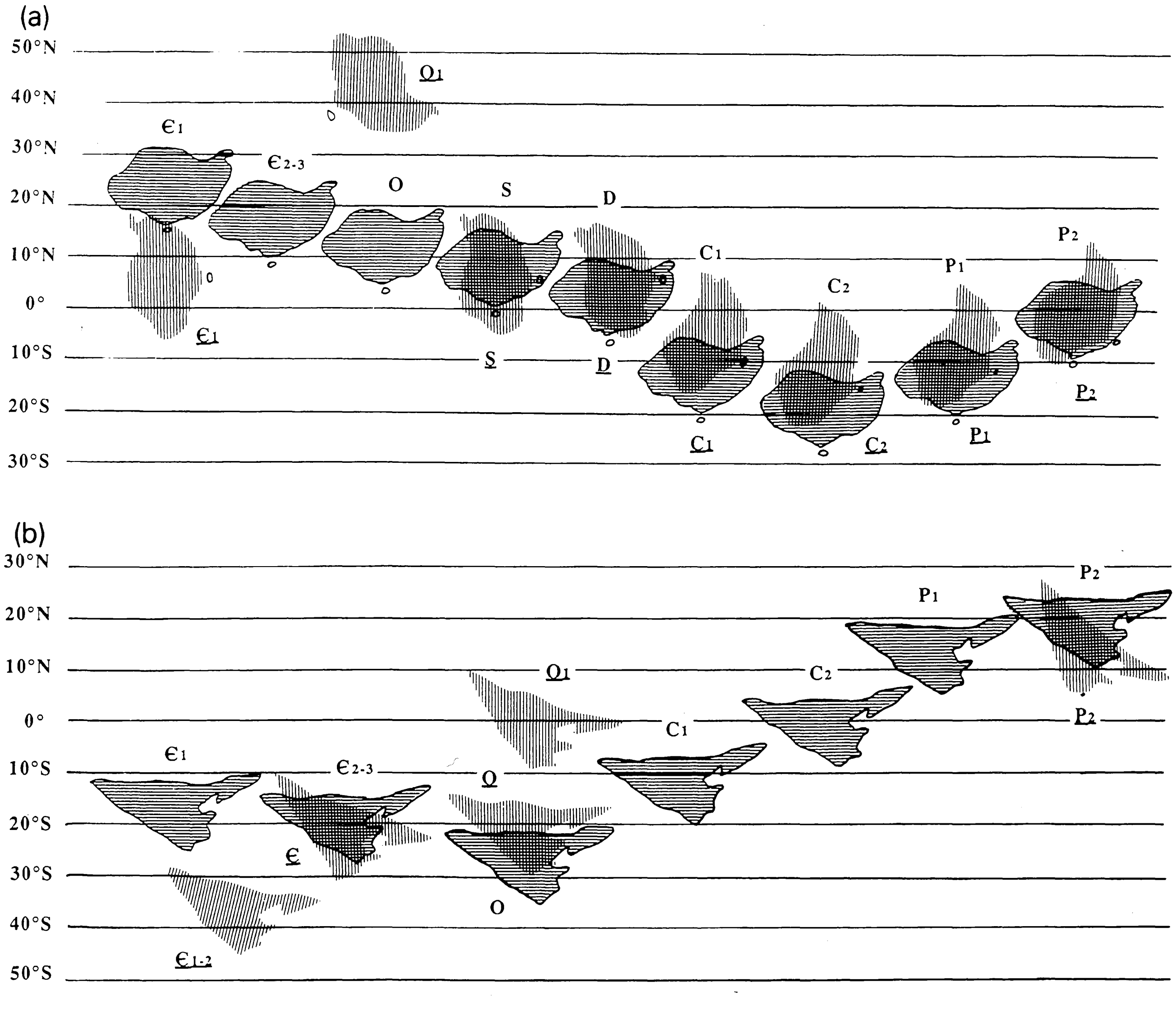


Figure 17 Schematic positions of the South China (a) and the North China (b) blocks through the Palaeozoic as derived from palaeoclimatic (horizontal shading) and palaeomagnetic (vertical shading) data, after Nie Shangyou (1991, fig.9).

of Afghanistan, the Lhasa and Western Qiangtang blocks with Shan-Thai Malaysia and Sumatra in a Cimmerian Continent in the sense of Šengör. Interestingly, he also points out that the Cathaysian flora was linked to the Gondwanan flora through Arabia and that evidence for a Cathaysian flora is also known from regions outside the established Cathaysian continents (see also Wang Naiwen,1984), e.g. in Turkey, Iraq, Saudi Arabia, India and New Guinea, thus suggesting some possible interaction between the "Cathaysian continents" and the Cimmerian-Gondwanan continents. A comparable conclusion of absence of an apparent boundary between Cathaysia and Gondwana is reached also by Smith (1988) from study of rugose corals, which likewise show intermixing of Cathaysian and Gondwanan faunas in the Lhasa block. Shi et al. (1995) interpret comparable evidence for marine faunal mixing to represent

Cimmeria's ongoing fragmentation from Gondwana and accretion to Cathaysia. Biogeographic controls on timing of dispersion and accretion are generally within the timespans specified above in the discussion of Šengör's and Scotese's papers. In short, Tarim collided with Kazakhstan in the latest Carboniferous-earliest Permian, North China with the arc complex of the Altaids in the Late Permian, South China with North China in the Late Triassic and Early Jurassic, the Western Qiangtang block with the Songpan-Ganzhi accretionary complex in the Triassic, and the Lhasa block with Qiangtang in the Jurassic. The Mongolo-Okhostk suture between North China and the Altaid complex represents a notable exception to the generally southward younging trend of suturing. It closes diachronously from Permian in the southwest to Late Jurassic to Early Cretaceous in the east.

Nie Shangyou proposes a late Early Permian rather than Late Permian breakup of Cimmeria from northern Gondwana, and also presents evidence for a Cathaysian flora from the Helmand and West Qiangtang fragments of the Cimmerian Continent. Contact was, thus, presumably established by the Late Permian. A summary of palaeoclimatic and palaeomagnetic constraints on Palaeozoic movements of the North and South China blocks is reproduced in Fig.17, subject to the premise that Early Palaeozoic magnetic polarities for the China blocks are not well-established and that South China is arbitrarily placed in the northern hemisphere and North China in the southern hemisphere during Cambrian times. There is considerable biostratigraphic evidence available to support the generally assumed Early Palaeozoic proximity of North China with Gondwana, but much of it may not be published in easily accessible papers (B. Nicoll, pers. comm.,1997). Alternatively, proximity between North China and Siberia during the Ordovician has been argued for (Cocks and Fortey,1990). Palaeoclimatic data suggest northward movement of North China after the Early Carboniferous. Nie Shangyou follows others (e.g. Burrett) in pointing to close biogeographic association of South China with Australia during the Early Palaeozoic, but cites evidence for an endemic Early Devonian fish fauna (Young,1981) and a distinctive Early Devonian unconformity as arguments for possible separation from Australia at that time. It seems that this assertion, based on meagre data, has since taken on a life of its own.

Metcalfe

In an impressive series of single author papers (Metcalfe,1984,1986,1988,1990,1991,1992,1993a,b, 1994a,b,1995,1996a,b,c; Metcalfe and Nicoll,1994) Metcalfe has developed a synthesis evolution of the wider Southeast Asian region which is both highly up-to-date and knowledgeable. Based on his first-hand experience of regional stratigraphy and palaeontology of eastern and southeastern Asia and constrained by available palaeomagnetic and palaeofacies data, Metcalfe has identified a multitude of pre-Cretaceous continental blocks (Fig.18) that were derived originally from the Greater India - Greater Australia margin of eastern Gondwana.

A Palaeozoic reconstruction of these blocks (Fig.19) includes from outboard to inboard and from Greater India to Australia: South China, the Tarim block (including the Kun Lun and Ala Shan terranes) and North China; Qaidam and Indochina; Qiangtang, Sibumasu and possibly the Hainan block; the Lhasa and West Burma-Woyla (formerly Mount Victoria Land) blocks. These blocks are thought to have fragmented from Gondwana and amalgamated/accreted to Laurasia in three main phases (Metcalfe,1996a) corresponding with closing/opening of three successive oceanic basins: Palaeo-Pacific - Palaeo-Tethys; Palaeo-Tethys - Meso-Tethys; Meso-Tethys - Ceno-Tethys (Fig.20).

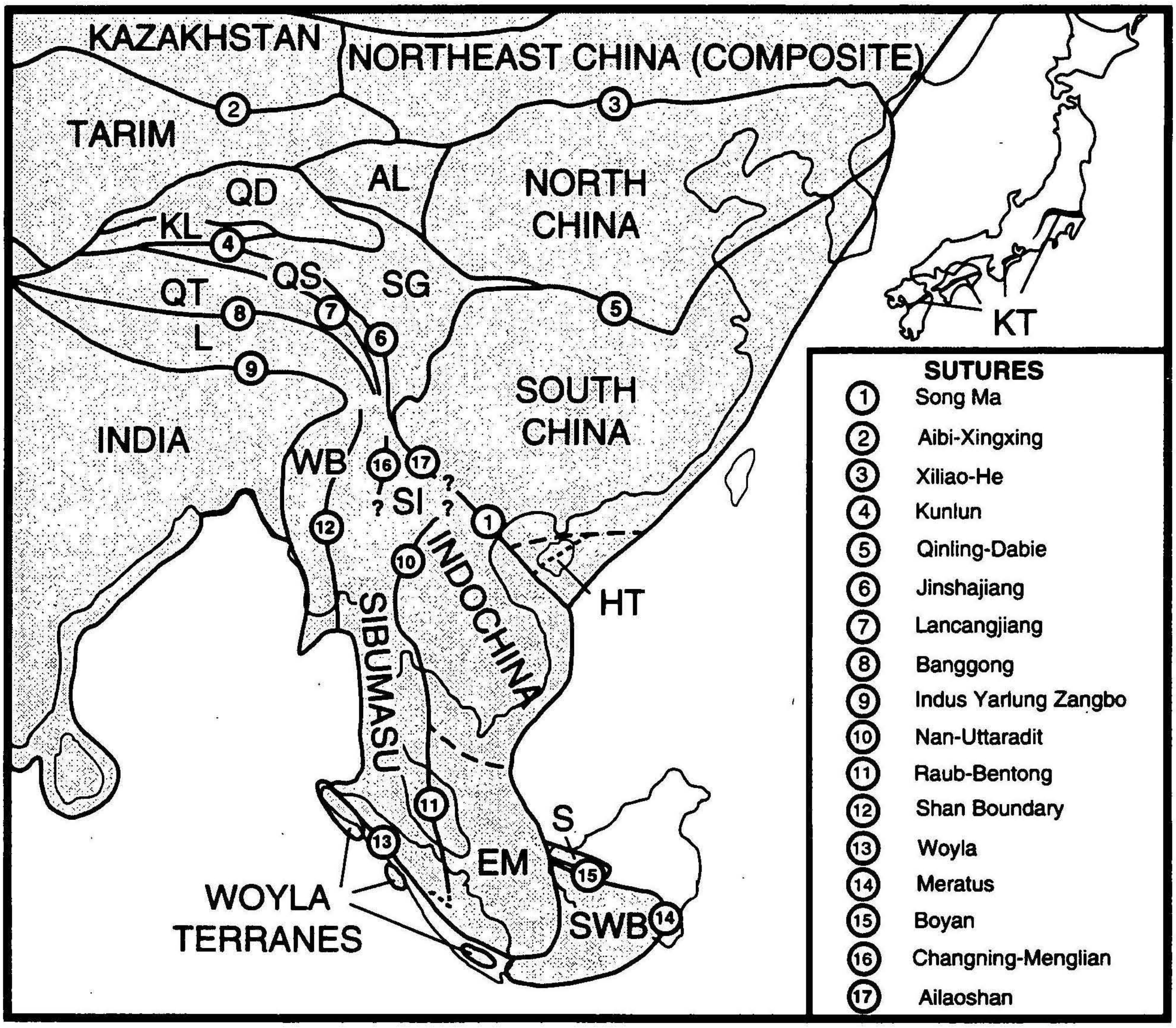


Figure 18 Distribution of principal continental terranes and sutures of eastern and Southeast Asia, after Metcalfe (1996a, fig.1). EM=East Malaya, WB=West Burma, SWB=South West Burma, S=Semitau Terrane, HT=Hainan Island Terrane, L=Lhasa Terrane, QT=Qiangtang Terrane, QS=Qamdo-Simao Terrane, SI=Simao Terrane, SG=Songpan-Ganzi accretionary complex, KL=Kunlun Terrane, QD=Qaidam Terrane, AL=Ala Shan Terrane, KT=Kurosewaga Terrane.

In the first phase the most outboard blocks - North China, South China, Indochina-East Malaya-Qamdo-Simao, Qaidam and Tarim - are thought to have separated during the Devonian (Metcalfe,1996b) or Late Devonian (Metcalfe,1996a,c: Fig.21), although Metcalfe (1994b) mentions an earlier Silurian to Early Devonian date, Metcalfe (1993a) a Silurian date, and Metcalfe (1988) an Early Carboniferous date. In the second phase blocks identified as part of Šengör's Cimmerian Continent (Sibumasu, Qiangtang and possibly Hainan) are thought to have separated by the Early-Middle Permian, and in the third phase the most inboard blocks (Lhasa and West Burma-Woyla) separated during Late Triassic to Late Jurassic. The time of fragmentation of some of these blocks seems disputable. Thus, the Lhasa block is included

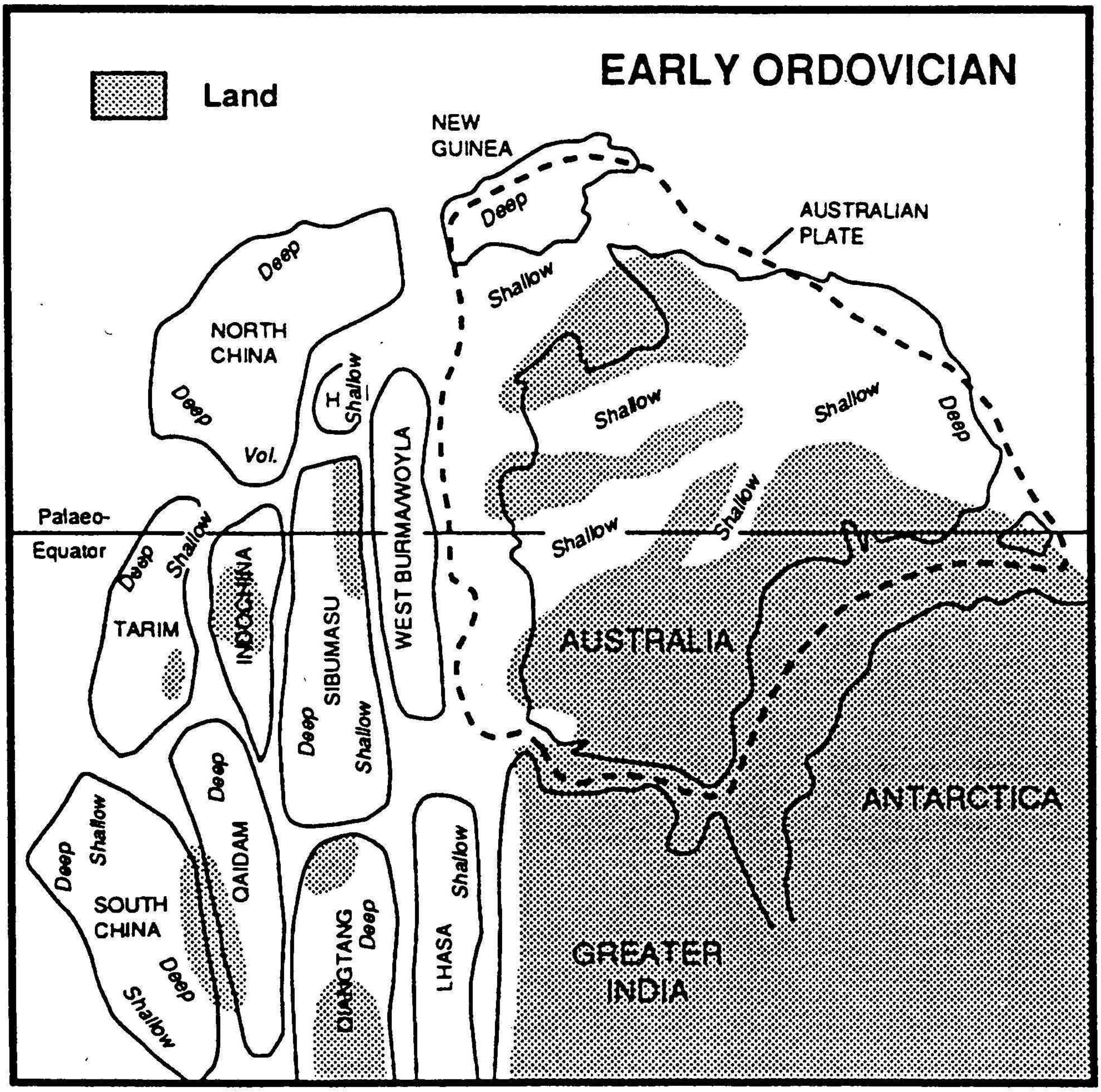


Figure 19 Reconstruction of northeastern Gondwana in the Early Ordovician, after Metcalfe and Nicoll (1994,fig.1) and Gorter et al. (1994, fig.15). H=Hainan Island.

alternatively within the third (Metcalfe,1996a,b,c) or the second rifting phase (Metcalfe and Nicoll,1994), whereas the Hainan block(s) are included within the second (Metcalfe,1996a; Metcalfe and Nicoll,1996b) or the first phase (Metcalfe,1996b,c). Metcalfe also identifies the Kurosegawa terrane as a possible "Australian" Gondwanan fragment, accreted to the Japanese part of Eurasia in the Late Jurassic.

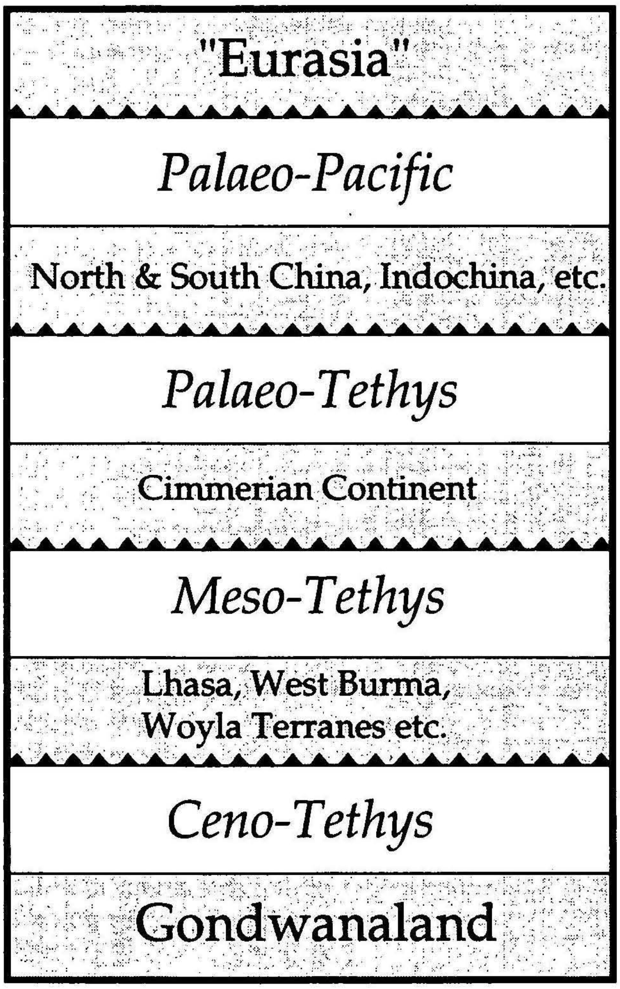


Figure 20 Schematic diagram showing the three continental slivers/collages of terranes, rifted from Gondwana and translated northward by opening and closing of three successive oceans, the Palaeo-Tethys, Meso-Tethys and Ceno-Tethys, after Metcalfe (1996a, fig.6).

The "first phase" Tarim-Kunlun-Ala Shan and Qaidam blocks are thought to have accreted to Kazakhstan-Siberia during the Permian, whereas South China and Indochina are thought to have amalgamated onto "Cathaysialand" during the Late Devonian-Early Carboniferous (Fig.22A). Cathaysialand and North China remained at low northern-to-equatorial latitudes during the Late Carboniferous and the Permian with further amalgamation of the "second phase" Sibumasu and Qiangtang blocks to Cathaysialand in the Late Permian-Early Triassic (Fig.22C) or Early Triassic (Metcalfe,1993a), which is in agreement with Archbold and Shi's (1996) interpretation based on brachiopod faunas for docking during the latest Permian-earliest Triassic. The North and South China blocks of Cathaysialand amalgamated and then accreted to Laurasia by Late Triassic-Early Jurassic times (Fig.22D). The "third phase" Lhasa and West Burma-Woyla blocks accreted to proto-Southeast

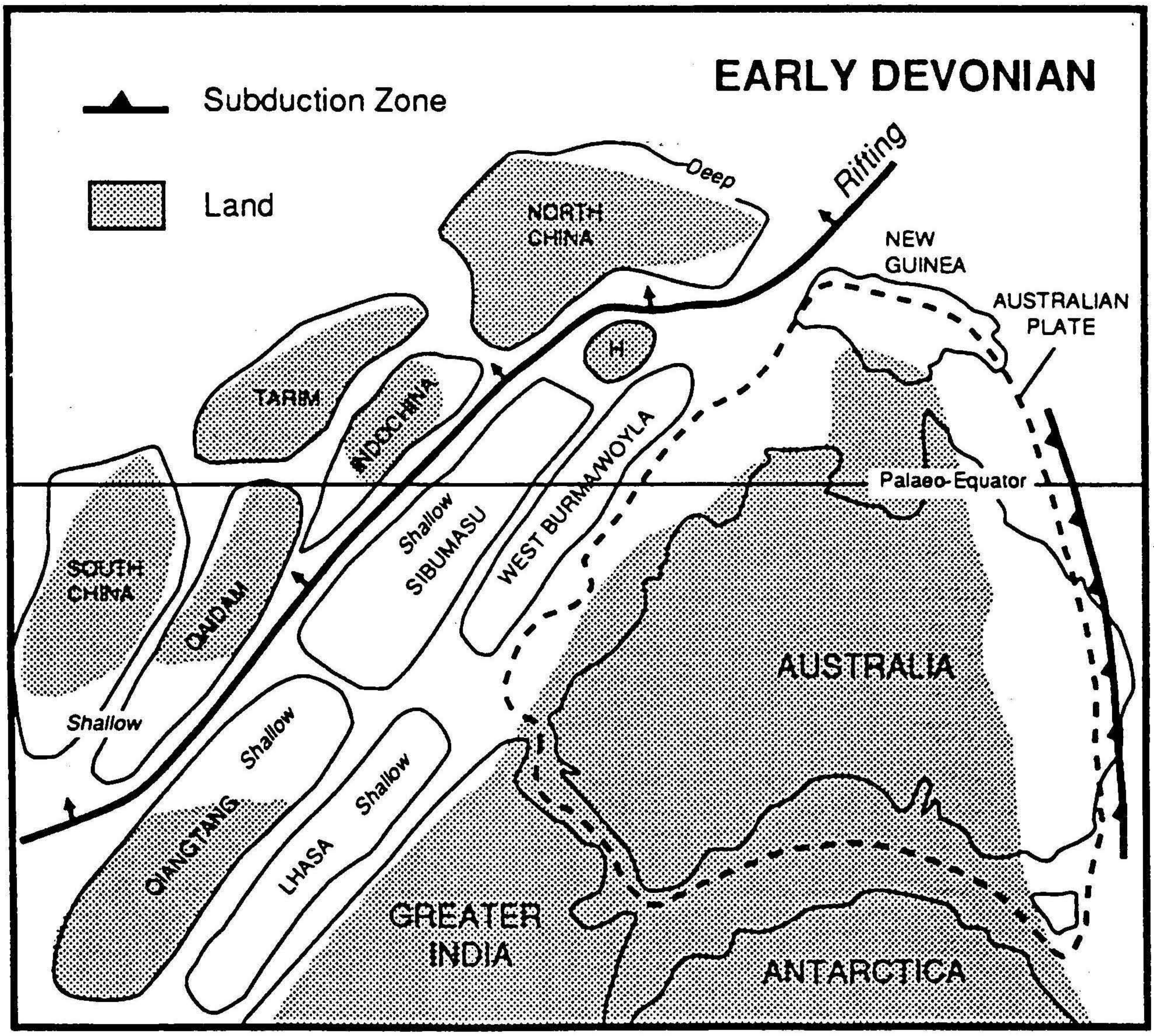


Figure 21 Reconstruction of northeastern Gondwana in the Early Devonian, after Metcalfe and Nicoll (1994, fig.3). H=Hainan Island.

Asia during the Cretaceous. A Gondwanan origin of Hainan is uncertain. Earlier cited evidence for Permian glacial activity appears not sustainable and preliminary palaeomagnetic results are equivocal in relation to a Gondwanan origin.

Some implications of Metcalfe's synthesis are notably at variance with models proposed by other authors, e.g. with some of the models discussed above:

- Kazakhstan is considered part of a Siberian-Kazakhstan block similar to an earlier and now abandoned model of Scotese and McKerrow (1990,1991), but abundant biostratigraphic evidence for an Early Palaeozoic connection with

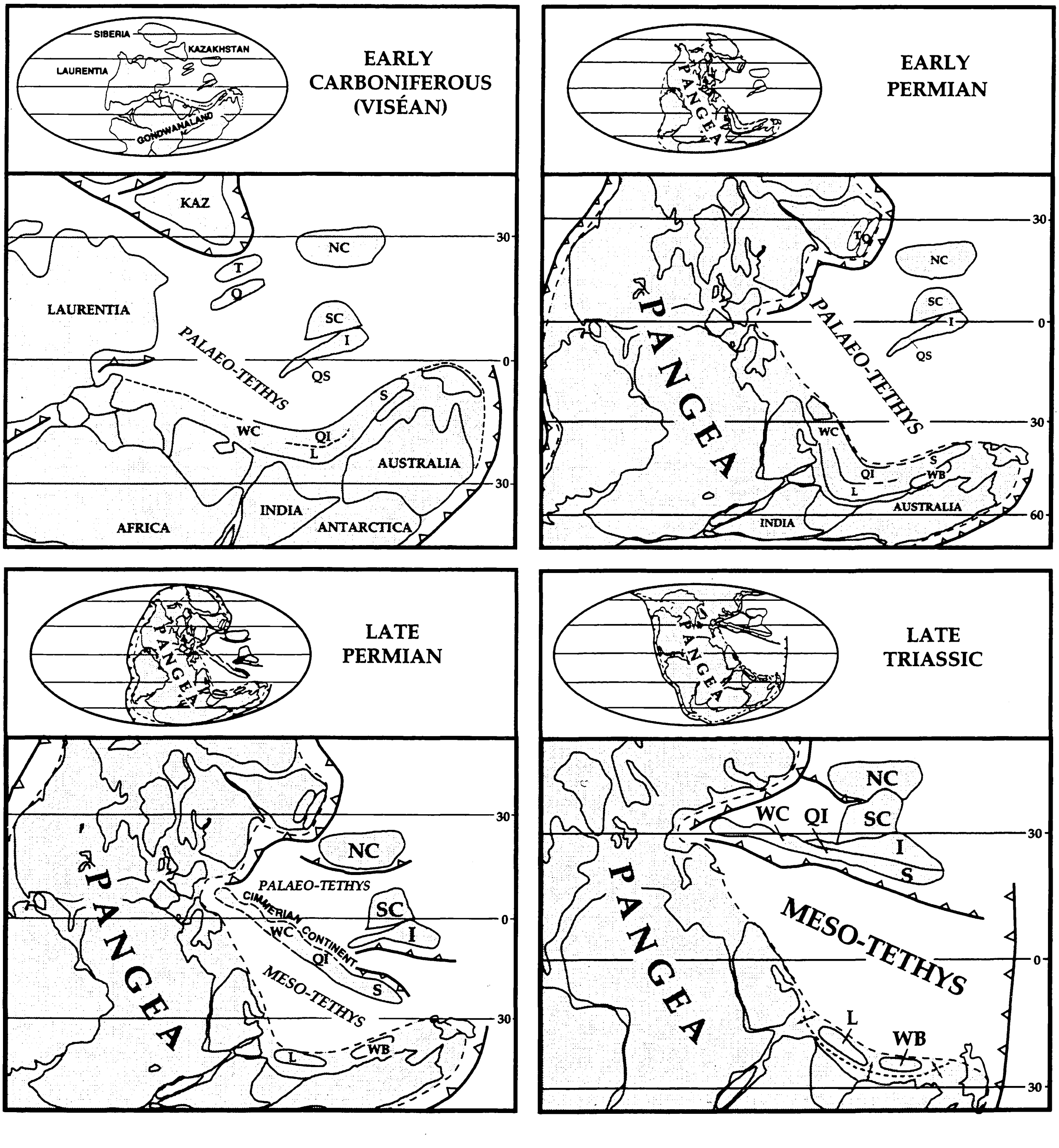


Figure 22 Palaeogeographic reconstructions of the Tethyan region for the Early Carboniferous, Early Permian, Late Permian and Late Triassic, after Metcalfe (1996a, fig.13).

northern Australia (Shergold,1995) is not discussed.

The West Burma-Woyla block has not been identified before as a probable Gondwanan fragment and Metcalfe's (1990) identification is tentative only. It is, however, hard to imagine that this fragment could have come from anywhere but Gondwana (B. Nicoll, pers. comm.,1997).

- The three-phase rifting model can be seen as an extension of Şengör's two-phase model with interpretation of the Waser-Banggong Cu - Nujiang oceanic incursion as a separate fragmentation event.
- An interesting and novel attempt has been made to show lithofacies constraints on the reconstructed Greater India-Greater Australia margin of Gondwana. However, such constraints cannot uniquely identify original co-locations. Apart from some palaeomagnetic constraints on palaeolatitudes, firm biostratigraphic constraints on co-location are advanced only for South China with the Himalaya-Iran region, for the Tarim with the North and South China blocks (Metcalfe,1994b), for Indochina with the North and South China blocks (Metcalfe,1993a), and for Sibumasu with the northwestern margin of Greater Australia.
- Arguments for an Early to Late Devonian (Metcalfe,1996a,b,c) rather than middle to Late Carboniferous (Şengör, 1984,1985), timing for the first rifting phase are based on the major Early Devonian unconformity of the western Australian margin, seen as evidence for extension, and the Givetian flooding onlap seen as a post-separation susbsidence phase (B. Nicoll, pers. comm.,1997). Devonian vertebrate faunas indicate, however, that the Cathaysian blocks were still in close proximity to or attached to Gondwana during the Devonian (Metcalfe,1996a), although Metcalfe (1994b) follows Burrett et al. (1990) in contending that South China was effectively isolated from other continental masses because of its high degree of Devonian floral and faunal endemism. Development of what is interpreted as Devonian to Triassic passive margin sequences along the southern margin of the South China block is the stronger of the arguments for a Late Devonian separation. Interpretation of the widespread occurrence of a conspicuous Late Devonian-Early Carboniferous unconformity on most Asian blocks as a breakup unconformity is disputable. It equally can be interpreted as a tectonic phase as part of Gondwana. Further, a Devonian counterclockwise rotation of Gondwana is suggested as a separation mechanism. Such rotation, however, is based on an interpretation of the Australian Late Palaeozoic APWP (e.g. Li et al.,1993) that can well be challenged as discussed in the palaeomagnetism section in part two of this review (Record 1996/52).
- Metcalfe (1996a,b,c) follows Şengör and Scotese and is in agreement with Archbold and Shi (1996) in dating the onset of the second rifting phase in northwest Australia as late Early Permian. Metcalfe (1996c) acknowledges, however, that extensional and rifting activity as early as the Late Carboniferous is well-established for at least the Indian part of northern Gondwana, with start of development of the East Indian Gondwana basins, extrusion of the Panjal Traps, and rifting in northern Pakistan (Pogue et al.,1992).
- Metcalfe differs from others in postulating accretion of a unified "Cathaysialand" rather than accretion of a loose aggregation of Cathaysian fragments. Also he seems inconsistent in asserting a Late Devonian-Early Carboniferous accretion of South China and Indochina along the Song Ma suture, but advancing structural and biostratigraphic evidence for an Early to middle, or middle, Carboniferous accretion.

Zonenshain

A magnificently informative and elegant overview of the plate tectonic evolution of northern, central and eastern Asia is presented in Zonenshain's opus magnum, published in the AGU Geodynamics Series (Zonenshain et al.,1990). This treatise on the evolution of the former USSR integrates in a single volume the many pioneering plate-tectonic ideas and studies formulated and produced by Zonenshain and his coworkers during the two decades following the plate tectonic revolution in the late sixties (e.g. Zonenshain,1973,1984; Zonenshain and Savostin,1981; Zonenshain and Natapov,1990; Zonenshain et al.,1984,1985,1990). This 'must-read' textbook describes in clear and accessible language a series of well-presented palinspastic reconstructions covering the whole of the Phanerozoic and in lesser detail the Proterozoic. The palinspastic framework is based mainly on motions of the East European and Siberian continental blocks which have been reconstructed from three data sources: (i) kinematic data from faults, folds and tectonics; (ii) palaeomagnetic data, mainly as compiled and summarised by Khramov; and (iii) geologically deduced trajectories of continental motion over hot spots. The motion of a few only of the smaller key blocks (Kazakhstan, Omolon) is reliably constrained by palaeomagnetic control. Most of the motions and configurations of the smaller blocks are either interpreted from palaeoclimatic and lithological data or are presented arbitrarily on the reconstructions.

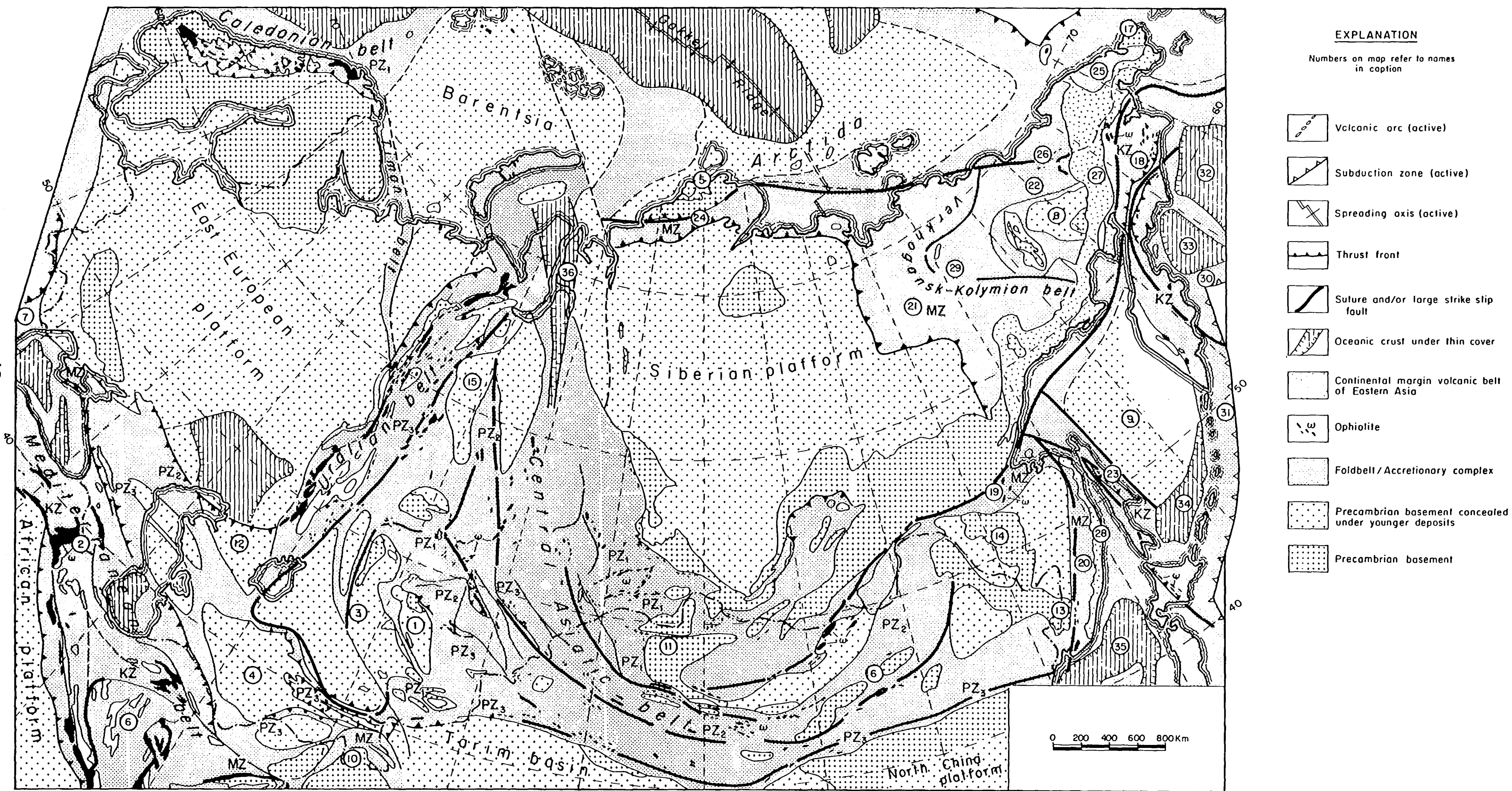
Figure 23A Continents, microcontinents and suspect terranes now constituting Asia and East Europe, shown in their present positions and Early Palaeozoic positions, after Zonenshain et al. (1990, fig.206). Lambert projection centered at 0°N, 90°E. Blocks in present positions are hatched, their Early Palaeozoic positions are shown by heavy lines. The Early Palaeozoic position of Gondwana is shown by dashed lines. Legend: A=Aldan shield, AR=Arabia, Ch=Chukotka, E=East Europe, I=India, IC=Indochina, K=Kazakhstan, NC=North China, S=Siberia, SC=South China, Other blocks and terranes: 1=Moesia, 2=Mugodzhar, 3=Dzirula, 4=Maker, 5=Iran, 6=Lut, 7=Ustyurt, 8=Karakum, 9=Tarim, 10=Kurgova, 11=South Pamirs, 12=Afghan, 13=Tibet, 14=Tom, 15=Tuva-Mongolian, 16=Barguzin, 17=Argun, 18=Amuria, 19=Sergeev, 20=East Sakhalin, 21=Chersky, 22=Okhotsk, 23=Omolon, 24=Talovo-Mainsky, 25=Koryakia, 26=Olyutorsky, 27=East Kamchatka, 28=Sea of Okhotsk, 29=Kara, 30=Shrenk.

These palinspastic reconstructions of the USSR are highly relevant to the identification and reconstruction of fragments that dispersed from Greater Australia-eastern Gondwana. Not only do the reconstructions trace the evolution of original Gondwanan fragments that now reside within or near to the Central Asian Fold Belt (e.g. Kazakhstan, Tarim-Karakul, Amuria, North China), but also of suspected Gondwanan fragments which are now situated in the northeastern (Okhotsk, Omolon, Chukotka) and northern part (Taimyr) of the former USSR, and which are probably related to terranes in the North American Cordillera (e.g. Wrangell, Alexander, Stikine). A tentative Early Palaeozoic reconstruction of the East European and Siberian (Aldan shield and Anabar Massif) cratons, Gondwana and the many original Gondwanan fragments that are now dispersed throughout Asia, is shown in Figure 23A. The reconstruction shows the Tarim-Karakum Massif opposite northwestern Australia, with Kazakhstan located further outboard. Indochina is located opposite western Greater Australia - northeastern Greater India. A series of seemingly undersized blocks - Tibet, Pamir, Afghanistan, Lut and Iran - is located outboard of Greater India-northeastern Arabia. North China is located far away from the north Australian margin of Gondwana, but the position of South China is not identifiable. Of considerable interest is the suggested position of the Okhotsk and Omolon blocks on the eastern margin of Australia. This infers that other Circum-Pacific terranes, including terranes now incorporated in the North American Cordillera, may have originated from this eastern margin. Zonenshain is, however, quite specific in relocating the Chukotka block near to Siberia and East Europe, whereas the original position of the Taimyr block is not identifiable on the figure.

An essential element of Zonenshain's Palaeozoic reconstructions (e.g. Fig.24) is the approximate north-south orientation of Gondwana, with Greater Australia positioned up north and located to the east of, and separated by, the Palaeo-Asian Ocean from the north-south aligned East European and Siberian cratons. The Palaeo-Asian Ocean contains a single north-south oriented subduction zone and a very long island arc, the Chingiz-Tuva Arc which bears some resemblance to the large arc systems postulated by Šengör (Kipchak Arc) and by Scotese. Continental blocks of Gondwanan origin that crossed the Palaeo-Asian Ocean are identified as the Tarim, Karakum, Tadzhik, Pamirs, Afghan, and Iran blocks and other microcontinents. Throughout the whole of the Palaeozoic a system prevailed whereby these microcontinental blocks separated from eastern Gondwana, moved west toward Siberia and became entrapped at a central subduction zone. Siberia and adjacent continental blocks approached the central subduction zone simultaneously from the west, so that both original Gondwanan and Siberian continental margins became juxtaposed near to the subduction zone. An evolutionary set of reconstructions for the Phanerozoic is detailed in the summary chapter. Some highlights of these reconstructions and associated descriptions are reproduced as far as they are relevant to fragmentation of Greater Australia's northwestern margin:

- In the Early-Middle Cambrian reconstruction Kazakhstan is already separated from the Tarim-Karakum margin of northwestern Greater Australia;
- The Tarim-Karakum block separates from northwestern Greater Australia in the Late Cambrian (Zonenshain et al.,1990: fig 189, Fig.25);
- In the Silurian there was considerable separation between Siberia-East Europe and Gondwana. Three oceanic

Figure23B [opposite page] Main structural elements of the wider USSR after Zonenshain et al. (1990, fig.1). Ancient massifs: 1=Atasu-Mointy, 2=Daralagez, 3=Kazakhstan-North Tienshan, 4=Karakum, 5=Kara, 6=Lut, 7=Moesia, 8=Omolon, 9=Sea of Okhotsk, 10=Pamirs, 11=Tuva-Mongolian, 12=Ustyurt, 13=Khankay, 14=Khingan-Bureya, 15=Khanty-Mansiisky, 16=Central Mongolian, 17=East Chukotka, 18=Koryak-Kamchatka, 19=Mongol-Okhotsk, 20=Sikhote-Alin, 21=Verkhoyansk, 22=Oloi-Alazei, 23=Sakhalin, 24=Taimyr, 25=Chukotka, 26=South Anui, Volcanic belts and magmatic arcs: 27=Okhotsk-Chukotka, 28=Sikhote-Alin, 29=Chersky, 30=Aleutian, 31=Kurol-Kamchatka, Marginal basins: 32=Aleutian, 33=Komandor, 34=South Okhotsk, 35=Japan Sea, 36=Onsky palaeo-ocean.


EXPLANATION
Numbers on map refer to names in caption
Volcanic arc (active)
Subduction zone (active)
Spreading axis (active)
Thrust front
Suture and/or large strike slip fault
Oceanic crust under thin cover
Continental margin volcanic belt of Eastern Asia
Ophiolite
Foldbelt/Accretionary complex
Precambrian basement concealed under younger deposits
Precambrian basement
Caledonian belt
Barentsia
Arctida
Gakkel Ridge
East European platform
Timan belt
Uralian belt
Siberian platform
Central Asiatic belt
Verkhoyansk-Kolymian belt
Mediterranean belt
African platform
Tarim basin
North China platform
0 200 400 600 800Km
60
70
80
90
100
110
120

spreading centers are identified: (i) the Palaeo-Ural Ocean between Siberia and East Europe; (ii) the Palaeo-Asian Ocean; and (iii) the newly formed Palaeo-Tethys between the Tarim-Karakum block and northwestern Gondwana. Kazakhstan converged during the Silurian with the Chingiz Island Arc (Zonenshain et al.,1990: fig 190, Fig.26) as did East Europe with North America to form Laurussia;

- During the Early Devonian the Palaeo-Asian, Palaeo-Ural and Palaeo-Tethys oceans reached maximum dimensions with maximum separation between the main continental collages. The Tuva-Mongolia block accreted to Siberia and Kazakhstan collided with the Chingiz Arc which ceased to be active. The Palaeo-Tethys continued to grow with further separation of Tarim-Karakum from Gondwana;
- In the Middle Devonian the Palaeo-Asian and Palaeo-Ural oceans started to close, but the Palaeo-Tethys widened with eastward movement of North China. Kazakhstan is close to southwestern Siberia and Tarim-Karakum is closing in to a subduction zone that separates it from Kazakhstan (Zonenshain et al.,1990: fig.193, Fig.27);
- During the Late Devonian and Early Carboniferous Siberia and East Europe converged with near closure of the Palaeo-Ural Ocean. The Tarim-Karakum and Tadzhik blocks are converging with Kazakhstan;
- During the middle Carboniferous Siberia converged with East Europe and Kazakhstan converged with both. The Amuria block, an accretion complex of the Mongolian Altaids and the Khingan-Bureya and Khankai Massifs, became attached to southeastern Siberia (Zonenshain et al.,1990: fig.195, Fig.28);
- By the Late Permian the Tarim-Karakum and Tadzhik block had collided with Kazakhstan, closing the Junggar basin. Amuria started moving toward Eurasia, closing the Mongolian-Okhotsk oceanic embayment. Iran and other fragments (presumably the Cimmerian Continent) had separated from Gondwana (Zonenshain et al.,1990: fig.197, Fig.29).
- In the Late Triassic North China collided with Eurasia. Iran and other Cimmerian blocks moved closer to Eurasia, thus decreasing the Palaeo-Tethys and opening the Meso-Tethys (Zonenshain et al.,1990: fig.198, Fig.30);
- In the Early Jurassic Iran approached Eurasia, but the Afghan and South Pamir blocks remained within the Tethys.
- By the Late Jurassic the Afghan and South Pamir blocks remained as the only fragments of Gondwana that had not yet accreted to southern Laurasia; Chukotka-Alaska and the Taimyr separated from North America (Zonenshain et al.,1990: fig.200, Fig.31);
- In the Early Cretaceous, the Afghan and South Pamir blocks approached Laurasia, the Taimyr block collided with Siberia and Chukotka-Alaska converged with the Siberian margin of Laurasia (Zonenshain et al.,1990: fig.201, Fig.32).
- In the middle Cretaceous the Pamir and Afghan blocks collided with southern Laurasia and Chukotka-Alaska collided with Siberia. Thus by the Aptian all continental and exotic terranes in the northeastern former USSR had gathered together and the Verhoyansk-Kolyma Fold Belt had formed during a very short timespan in the Early Cretaceous.

Zonenshain's plate tectonic analysis of the USSR (Zonenshain et al.,1990) does not consider the original location of the South China block versus Gondwana, nor its movements after separation. Such information had been presented in an earlier series of global reconstructions (Zonenshain et al.,1985). These were developed along the same lines as the reconstructions detailed above, but are presented in an arguably more consumable way as "whole-globe" Lambert equal area projections. These reconstructions (Fig.33 A-K), cover the Cambrian to the Late Triassic and add highly informative detail to the palinspastic reconstructions of Zonenshain et al. (1990). The whole-globe figures demonstrate quite clearly the close equatorial grouping of the major continental blocks, North America - Siberia - Europe - East Gondwana, and the large Palaeo-Pacific Ocean or Panthalassa, with its branching Iapetus and Palaeo-Asian oceans separating the major continental blocks. Major drift of the continents occurred during the Ordovician to Devonian with Siberia drifting to high northern latitudes, although high Devonian latitudes for Siberia are not acceptable on biostratigraphic grounds (G. Young, pers. comm.,1997), Europe drifting west to collide with North America before the Devonian, and eastern Gondwana drifting eastward, thus resulting in maximal continental separation during the Devonian. The Cambrian and Early Ordovician reconstructions show the co-located North China, Korea and South China blocks directly opposite northern Greater India, with South China close to the Tarim block (Fig.33A,B). North China starts to move away during the Ordovician (Fig.33B), but does not noticeably separates from South China-Korea until the Silurian-Devonian (Fig.33E), with South China-Korea separating from Greater Australia during the Devonian (Fig.33F). By the Late Carboniferous North and South China have

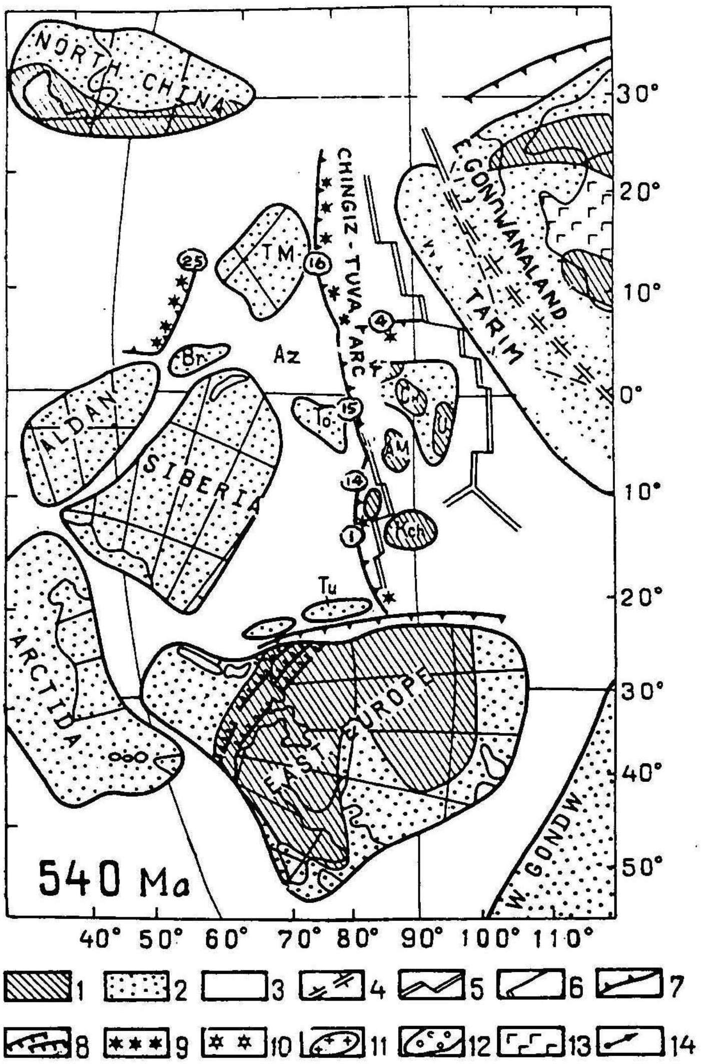


Figure 24 Palinspastic reconstruction of the USSR territory for 540 Ma, after Zonenshain et al. (1990, fig.188). The base map is the absolute reconstruction by Zonenshain et al. (1985). Lambert projection centered at 0°N, 90°E. Legend: 1=dry land, 2=shallow sea, 3=oceanic floor, 4=continental rift, 5=spreading axis, 6=transform fault, 7=subduction zone, 8=folding and metamorphism (collision zone), 9=calc-alkaline volcanism, 10=intraplate volcanics, 11=granitic batholith and gneissic-granite dome, 12=molasse basin, 13=flood basalts, 14=palaeomagnetic vector, 15=strike-slip motion, 16= directional to the geographical North Pole. Palaeolatitudes are shown. Precambrian massifs and exotic terranes: A=Alazei, Af=Afghan, Al=Altay, AM=Atasu-Mointy, B=Baisun, Br=Barguzin, Ch=Chu, Chr=Chersky, CK-Chukotka, CM=Central Mongolian, CP=Central Pamir, ES=East Sakhalin, Ju=Junggar, KhB=Khingan-Bureya, Kch=Kolchetav, Ku=Kutgovat, LK=Lesser Kuril, Ma=Maker, Mi=Moesia, Mu=Mugodzhar, Okh=Okhotsk, Ol=Olyutorsky, Om=Omolon, SO=Sea of Okhotsk, SP=South Pamirs, T=Tien Shan, TC=Transcaucasian, TM=Tuva-Mongolian, Tmt=Taimyr, To=Tom, U=Ulutau. Oceanic basins: AK=Akdam, Az=Palaeo-Asiatic, C=Canadian, Ca=Per-Caspian, EA=Eurasian, GC=Great Caucasus, M=Makarova, MO=Mongol-Okhotsk, PT=Palaeo-Tethys, SA=South Anyui, TB=Turkestan. Volcanic arcs and belts: 1=Chingiz, 2=Stepnyak, 3=Bet-Pak-Dala, 4=North Tien Shan, 5=South Tien Shan, 6=Mariev, 7=Marginal belt of Kazakhstan, 8=North Balkhash, 9=Balkhash, 10=Gissar, 11=Beltau-Kurama, 12=Valerianosvsky, 13=Ili, 14=Salair, 15=Minusinsk, 16=Tuva, 17=Rudny-Altay, 18=Zharma, 19=Saur, 20=South Mongolian, 21=Magnitogorsk, 22=Chara, 23=Tom-Kolyvan, 24=West Sayan, 25=Great Caucasus, 26= Inner Mongolian, 27=Eurasian, 28=Uyandina-Yasachnaya, 29=Sikhote-Alin, 30=Lesser Caucasus, 31=Anui, 32=Okhotsk-Chukotka, 33=Sikhote-Alin, 34=Irunei, 35=Bowers, 36=Kamchatka, 47=Alburz, 38=Carpathian, 39=Great Caucasus, 40=Hindukush, 41=Koni-Murgal, 42=Oloi, 43=Olyutorsky, 44=Anadyr-Bristrol, 45=Adjaro-Trialetian, 46=Iran, 47=Aleutian. Above legend applies also to Figures 25 to 33, listed hereunder.

amalgamated (Fig.33H), with accretion of the combined block to Laurasia by the Late Triassic (Fig.33K). Zonenshain et al. (1985) specifies the duration of the various palaeo-oceans. The Palaeo-Pacific ocean existed during the Palaeozoic in the western hemisphere. In the eastern hemisphere, the lapetus existed from Late Proterozoic till amalgamation of East Europe (Baltica) and North America in the Silurian-Devonian. The Palaeo-Ural ocean existed from the Late Cambrian to the Carboniferous-Permian with then amalgamation of Siberia and Laurussia (East Europe) into Laurasia. The Palaeo-Asian ocean existed from the Late Proterozoic till the middle Ordovician, and the Palaeo-Tethys existed from the middle Ordovician till the Early Triassic.

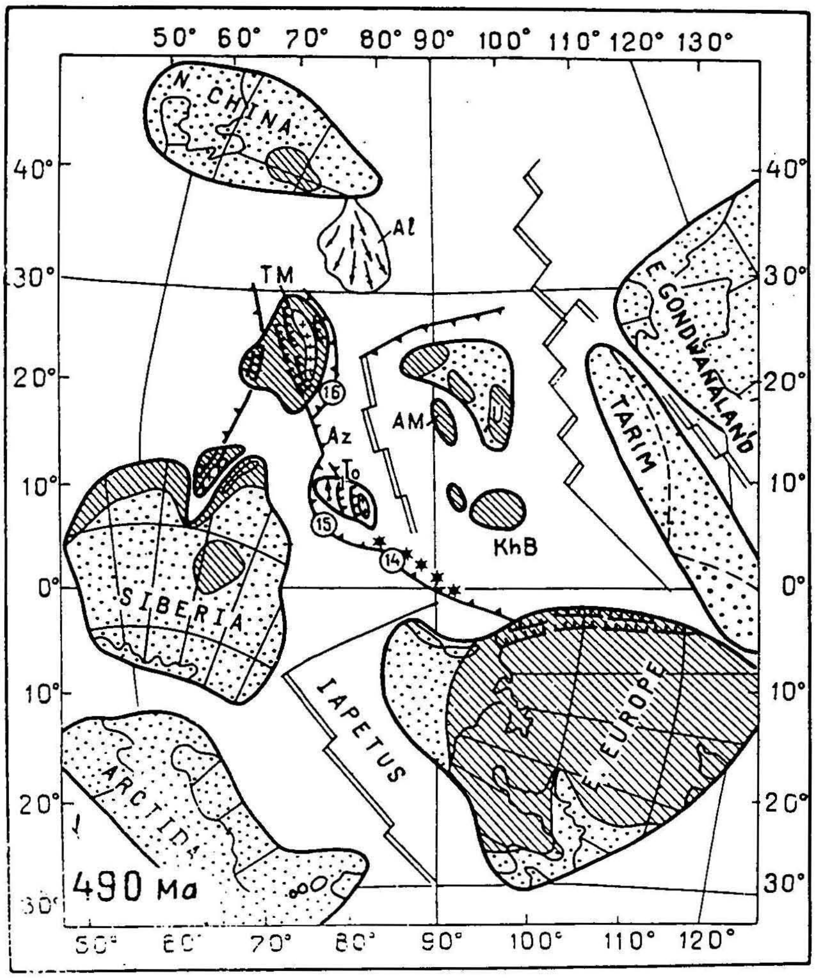
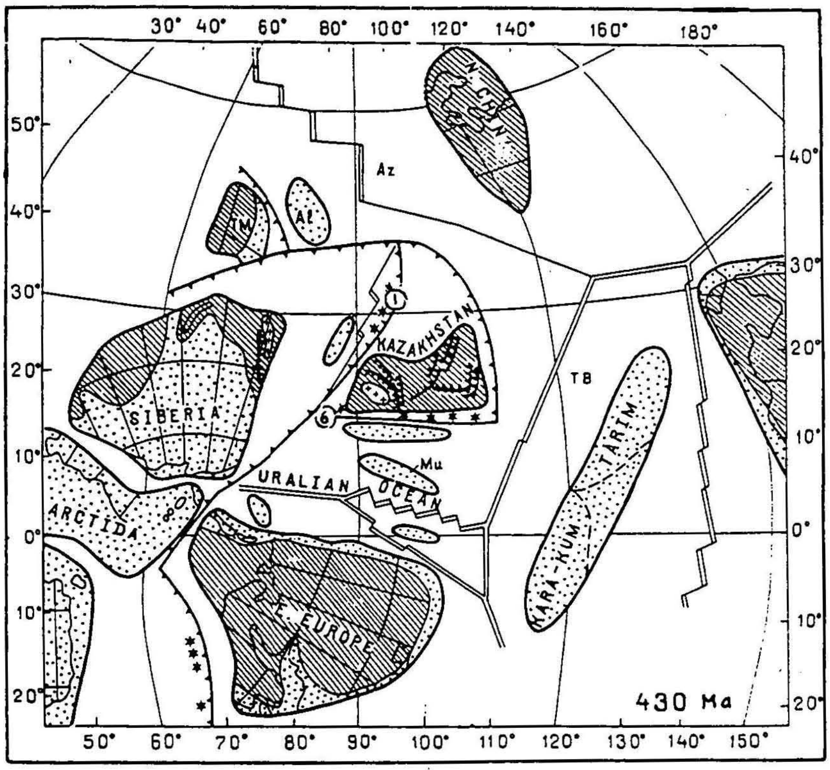


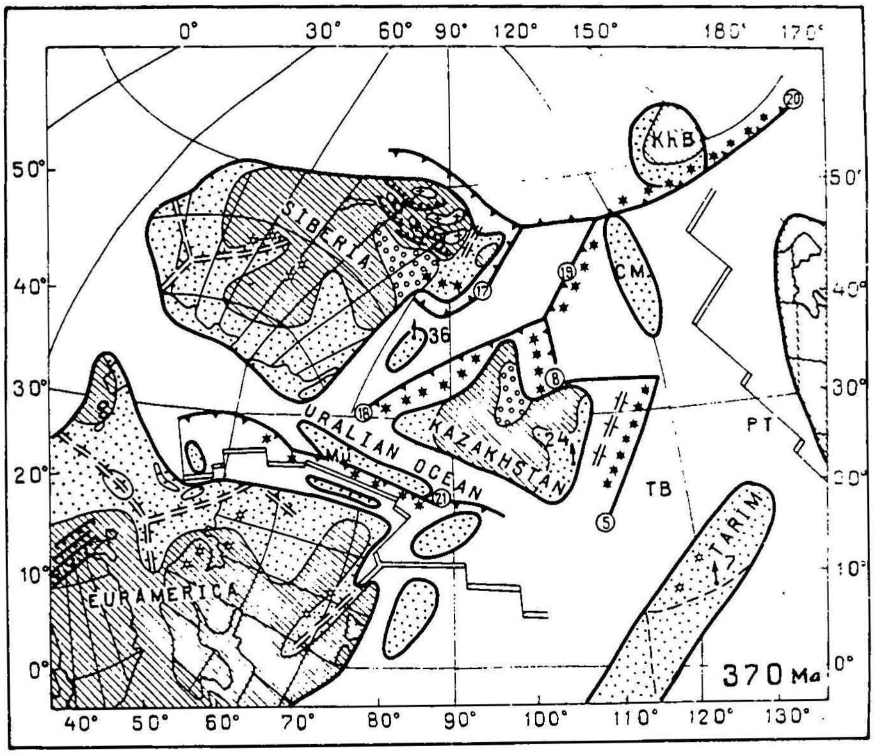
Figure 25 Palinspastic reconstruction of the USSR for 490 Ma, after Zonenshain et al. (1990, fig.189). See Figure 24 for legend.

Clearly the lifespan of the Palaeo-Tethys as defined by Zonenshain and the various other authors described above are markedly different. Şengör's definition spans the Early Carboniferous to Early Cretaceous, Scotese argues that a Şengör-type Palaeo-Tethys existed throughout the Palaeozoic. Metcalfe is less outspoken on the lifespan of the four successive oceans but his views are closer to Scotese in identifying that a Palaeo-Tethys ocean had already come into existence by the Silurian-Devonian.

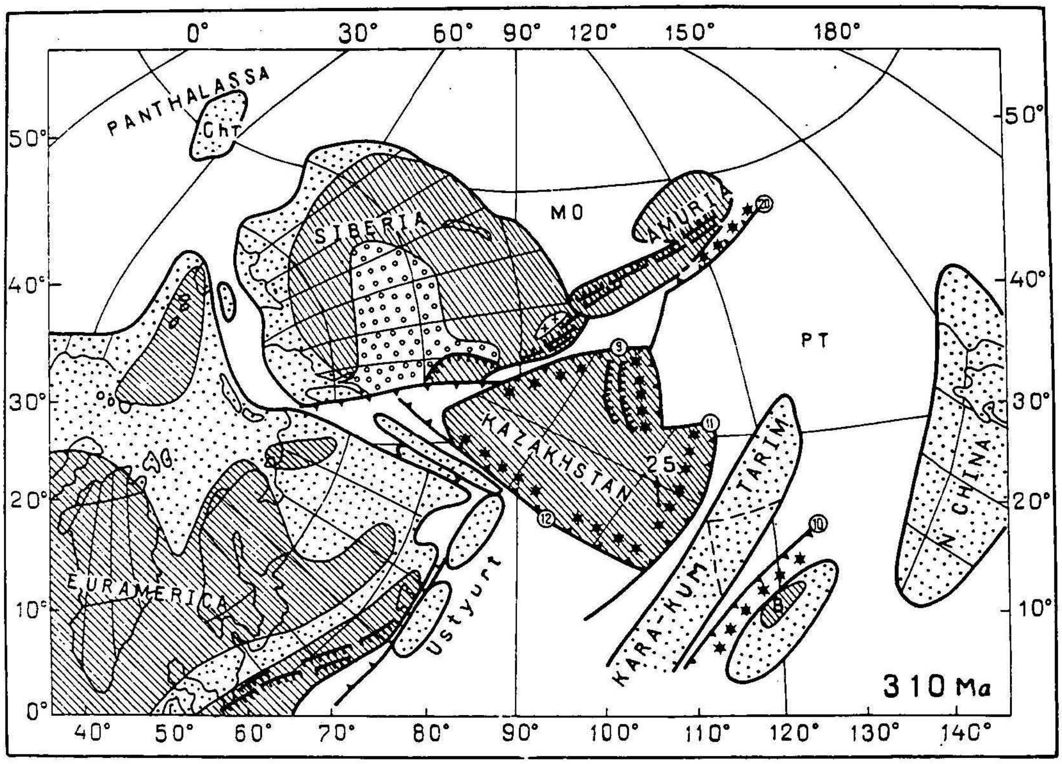
IGCP Project 238 "Geodynamic Evolution of Paleoasian Ocean"

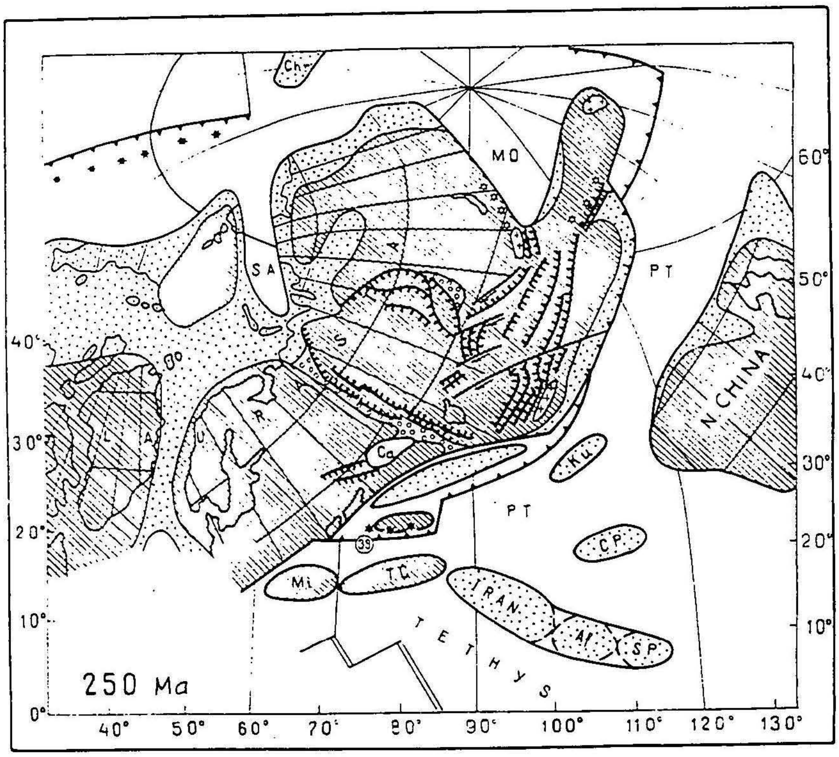
Very informative proceedings of the final 1993 symposium of this highly successful International Geological Correlation project have been published in a special volume of Russian Geology and Geophysics (Vol 35, Nos 7-8, 1994). This volume summarises current knowledge on, and interpretations



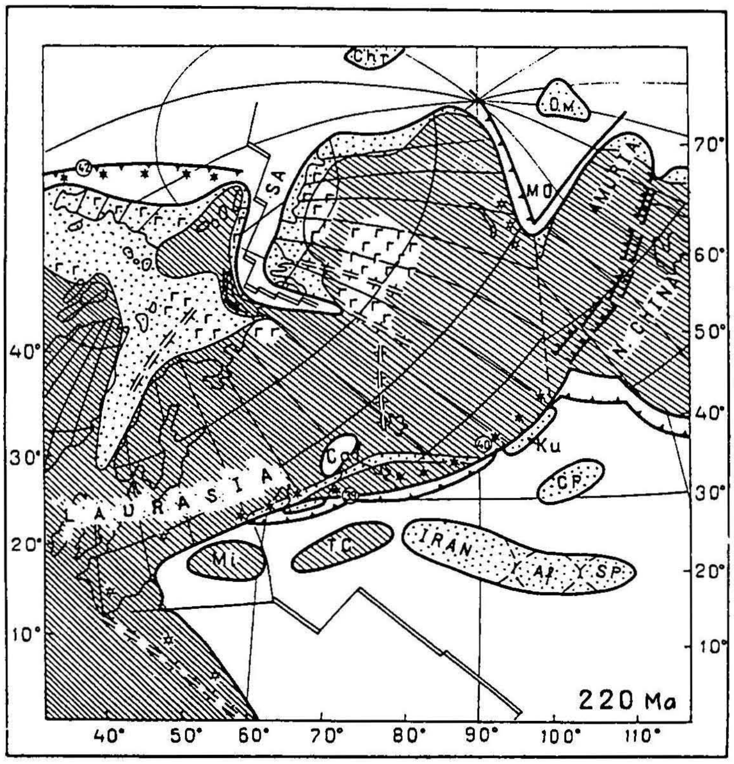


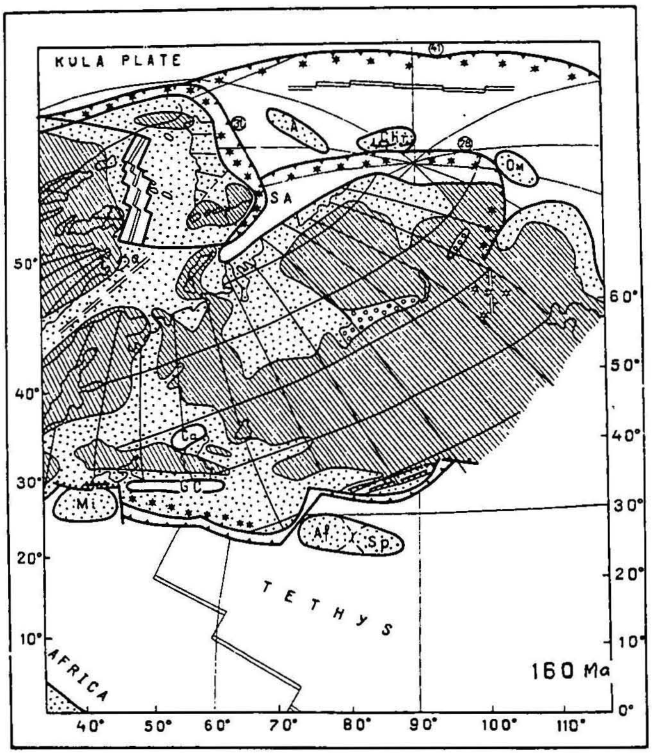
Figures 26,27 Palinspastic reconstructions of the former USSR for 430 Ma [top] and 370 Ma [bottom], after Zonenshain et al. (1990, figs 190,193). See Figure 24 for legend.





Figures 28,29 Palinspastic reconstructions of the former USSR for 310 Ma [top] and 250 Ma [bottom], after Zonenshain et al. (1990, figs 195,197). See Figure 24 for legend.





Figures 30,31 Palinspastic reconstructions of the former USSR for 220 Ma [top] and 160 Ma [bottom], after Zonenshain et al. (1990, figs 198,200). See Figure 24 for legend.

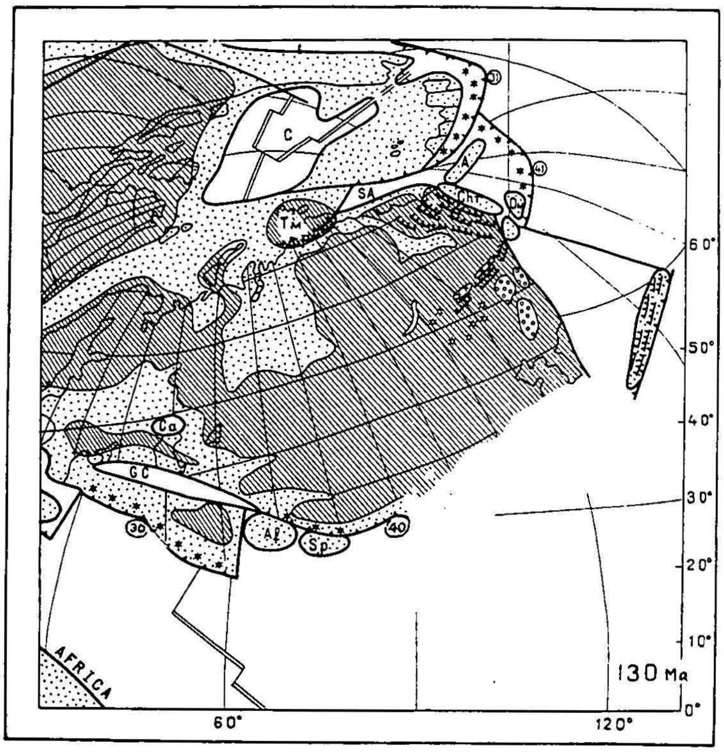
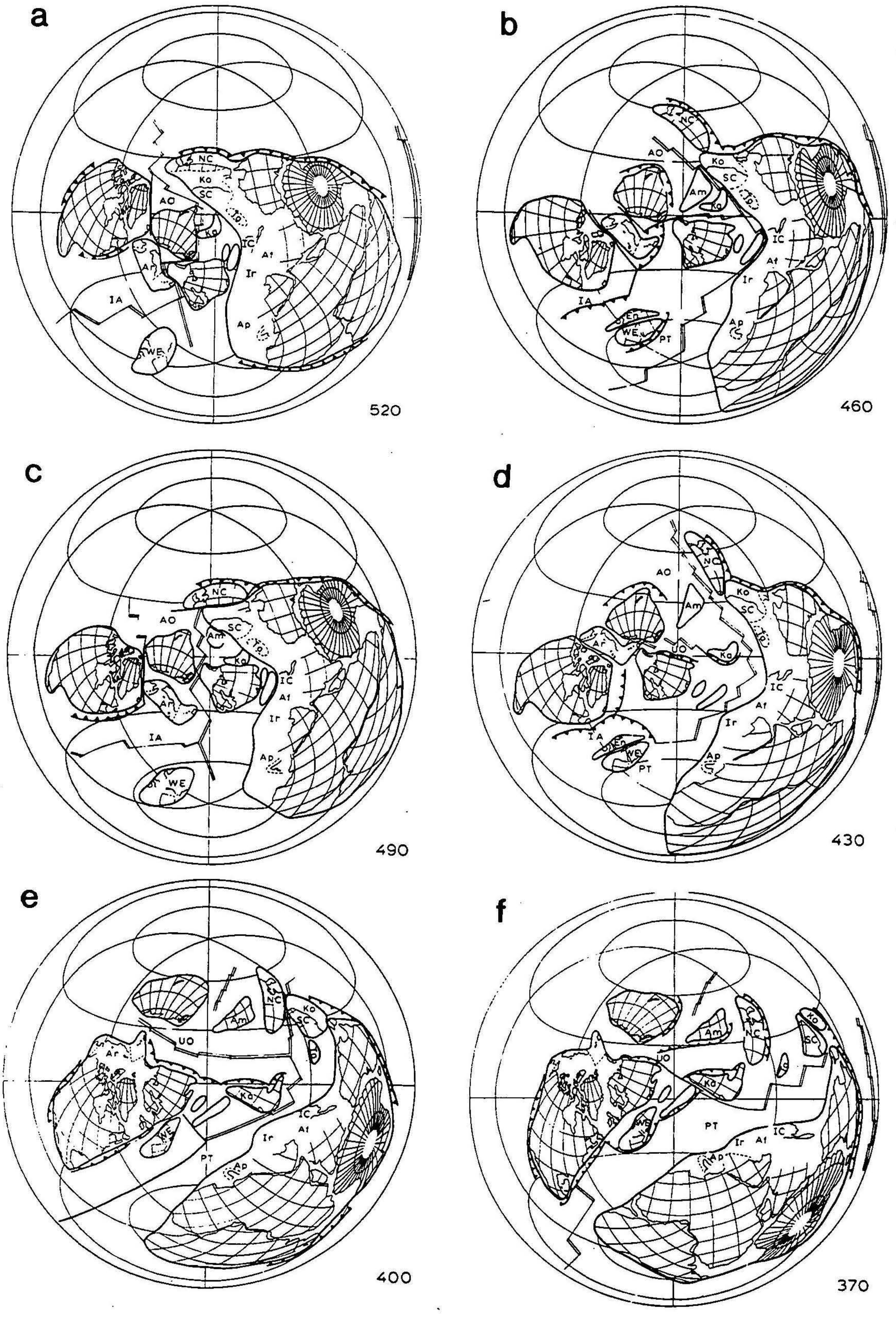


Figure 32 Palinspastic reconstruction of the former USSR for 130 Ma, after Zonenshain et al. (1990, fig.201). See Figure 24.

of, the evolution of central Asia from a Russian point of view. Discussion of Šengör et al.'s (1993,1994) model for the tectonic evolution of the Altaids figures prominently in the symposium proceedings. This model is criticised on three main points (Dobretsov et al.,1994): (i) the Palaeoasian Ocean had a complex structure with multiple island arcs, rather than the single extensive Kipchap Arc described by Šengör et al.; (ii) many continental fragments were involved in the process of accretion to southern Laurasia, in contrast to Šengör et al's exclusive emphasis on the oceanic nature of the Kipchak Arc; and (iii) new palaeomagnetic data for the Early and Middle Palaeozoic (Didenko et al.,1994, Pecherskii et al.,1994) are not consistent with Šengör et al.'s reconstructions.

Two key papers of the proceedings volume discuss the geodynamic evolution of the western (Berzin et al.,1994: fig.1, Fig.34) and eastern (Belichenko et al.,1994: fig.1, Fig.35) segments of the Palaeoasian Ocean on the basis of newly compiled maps. The model of Berzin and coworkers identifies from geological and palaeomagnetic evidence the former existence, during the Late Riphean-Cambrian and the Ordovician-Carboniferous, of two individual oceans with migration of many microcontinents and accretion to the Siberian and Baltic cratons. Some of these microcontinents originated from the Siberian craton during the Riphean, e.g. the Sangilen-East Sayan, Tuva-Mongolian and Tomsk blocks. Most originated from Gondwana in separate phases of separation: the Altai-Mongolian and Atasu-Mointi blocks during the late Riphean or Vendian, and Kazakhstan, Tarim and other adjacent cratonic blocks during the Palaeozoic. The Middle Devonian is emphasised as a period of considerable restructuring, although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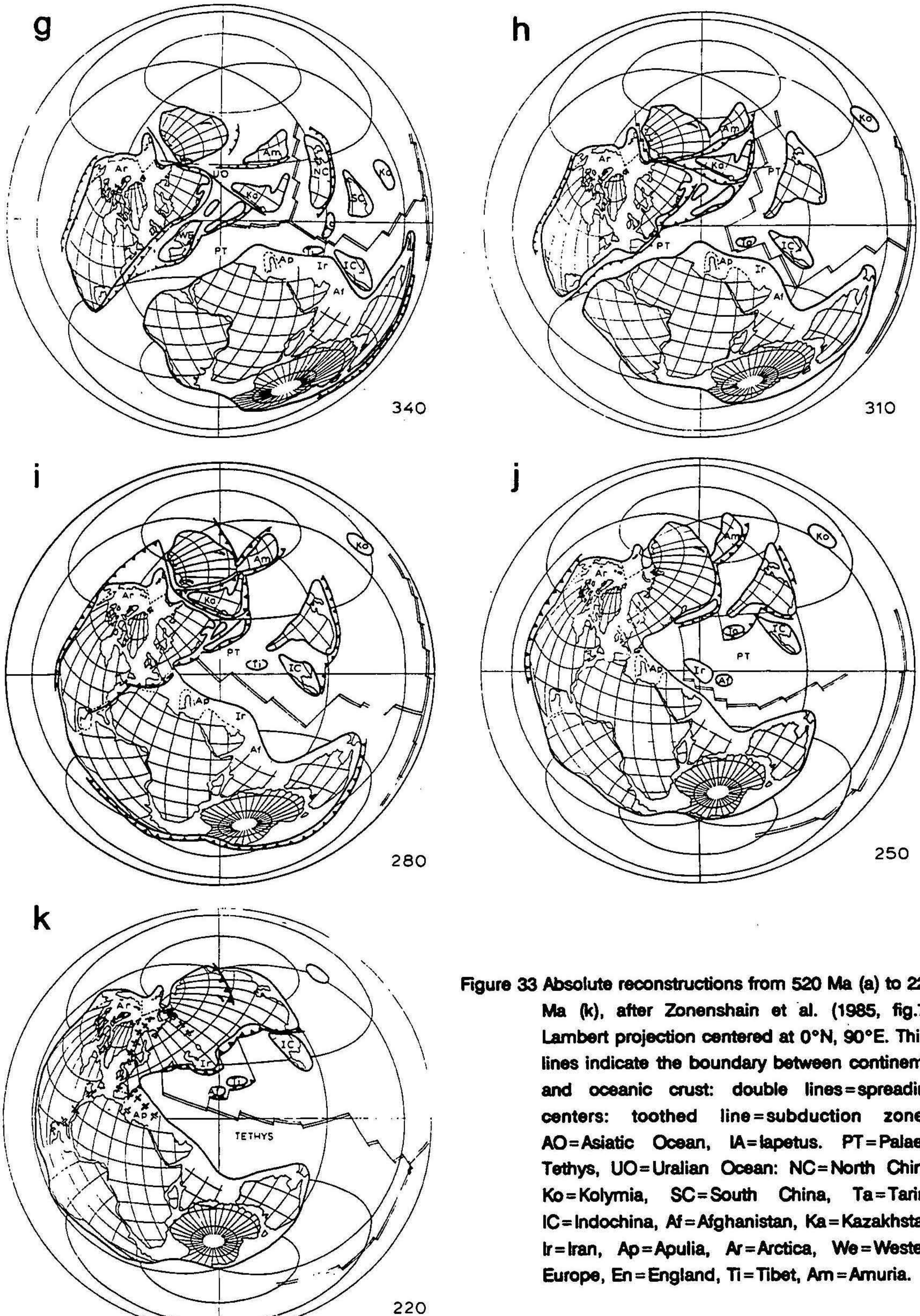


Figure 33 Absolute reconstructions from 520 Ma (a) to 220 Ma (k), after Zonenshain et al. (1985, fig.7). Lambert projection centered at 0°N, 90°E. Thick lines indicate the boundary between continental and oceanic crust: double lines=spreading centers: toothed line=subduction zones. AO=Asiatic Ocean, IA=Iapetus. PT=Palaeo-Tethys, UO=Uralian Ocean: NC=North China, Ko=Kolymia, SC=South China, Ta=Tarim, IC=Indochina, Af=Afghanistan, Ka=Kazakhstan, Ir=Iran, Ap=Apulia, Ar=Arctica, We=Western Europe, En=England, Ti=Tibet, Am=Amuria.

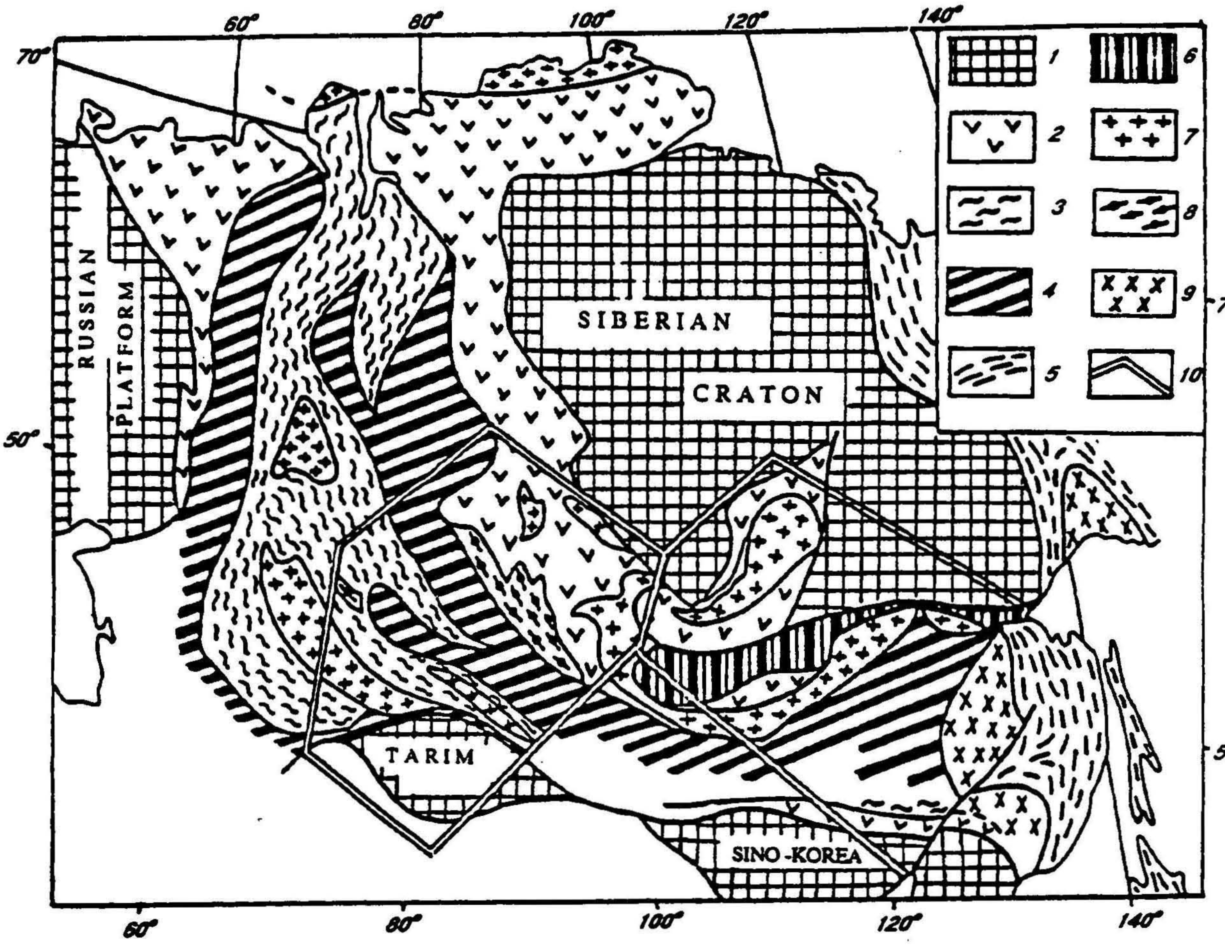


Figure 34 Outline of major tectonic zones around the Siberian craton and areas of geodynamic maps produced as part of IGCP Project 238, after Berzin et al. (1994, fig.1). 1=cratons; 2-6=accretion-collision systems with complexes of oceanic crust, island arcs and microcontinents; 2=P_{r3}-CB; 3=CB-S; 4=O-C_1 (up to T-P in the southeast); 5=Pz_3; 6=undifferentiated Pz-Mz; 7-9=microcontinents and Precambrian sialic blocks; 7=Laurasian groups; 8=Gondwanan groups; 9=others; 10=map boundary.

it is not clear whether this implies a phase of accretion to Laurasia or fragmentation from northern Gondwana, with closure of the western Paleoasian Ocean during Early-middle Carboniferous. Collisional and post-collisional magmatic phases in southern Laurasia are established for the Devonian, Carboniferous-Early Permian and Late Permian-Triassic and may relate to three phases of accretion. The model of Belichenko and coworkers for the eastern segment of the Palaeoasian Ocean also emphasises multiple accretion phases, although their timing is in part at variance with Berzin et al.'s model. Thus the Barguzin microcontinent (Belichenko et al.,1994: fig.1, Fig.35) is thought to have accreted to the Siberian craton prior to the Devonian and probably during Ordovician-Silurian rather than Riphean or Vendian as postulated by Zonenshain et al. (1990) and by Berzin et al. (1994). Final closure of the eastern part of the Palaeoasian Ocean, the Mongolo-Okhotsk Basin, proceeded from Permian in the western part, through Permo-Triassic in the central part, to Late Jurassic in the east.

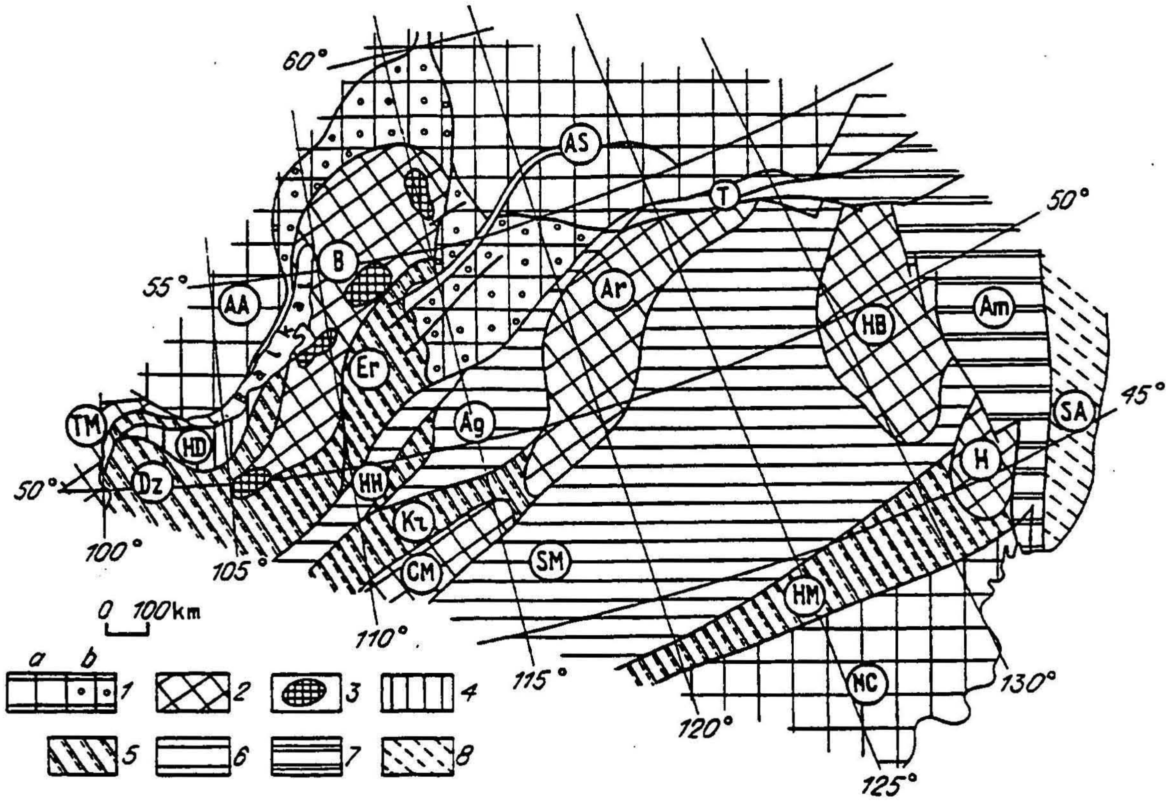


Figure 35 Palaeotectonic subdivisions of the eastern Altay-Sayan Okhotsk-Mongol fold belts, geodynamic map produced as part of IGCP Project 238, after Belichenko et al. (1994, fig.1). Palaeotectonic subdivisions: 1=stable (a) and Riphean-Early Palaeozoic active (b) cratons; 2=microcontinents; 3=Early Precambrian horsts within microcontinents; 4-8=terranes: Late Precambrian (4), Early Palaeozoic (5), Middle-Late Palaeozoic (6), Mesozoic (7) and Cenozoic (8); in circles: cratons: AA=Angara-Anabar; AS=Aldan-Stanovol; NC=North Chinese; microcontinents: Ar=Argun; B=Barguzin; CM=Central Mongolian; H=Khanka; HB=Khingan-Bureya; terranes: Ag=Aginsk; Am=Amur; Dz=Dzhida; Er=Eravnin; HD=Khamar-Daban; HH=Khnagai-Khentei; KR=Kerulen; SA=Sikhote-Alin; SM=South Mongolia; T=Tukuringra.

Didenko et al. (1994) present a mainly palaeomagnetically-based geodynamic model for evolution of the Central Asian Palaeozoic oceans, dispersion of Gondwanan fragments, and accretion to the Siberian craton, which is very relevant to the current study on the evolution of northwestern Greater Australia. Didenko et al. identify central Asian fragments of Gondwanan origin (Didenko et al.,1994: fig.1, Fig.36), reconstruct their original location on the northeastern margin of Gondwana (Fig.37A) and describe the evolution of their fragmentation and accretion to the Siberian craton (Didenko et al.,1994: figs 3-9, Fig.37B-H). The reconstructions are shown in a palaeolatitudinal framework. A notable aspect is the general east-to-west movement of the fragments: as a note of caution such movements are palaeomagnetically indeterminate.

Didenko et al. (1994) follow other Russian authors (Berzin et al.,1994; Belichenko et al.,1994) with a two-stage oceanic evolution model: (i) development of a Palaeoasian Ocean from Late Riphean to

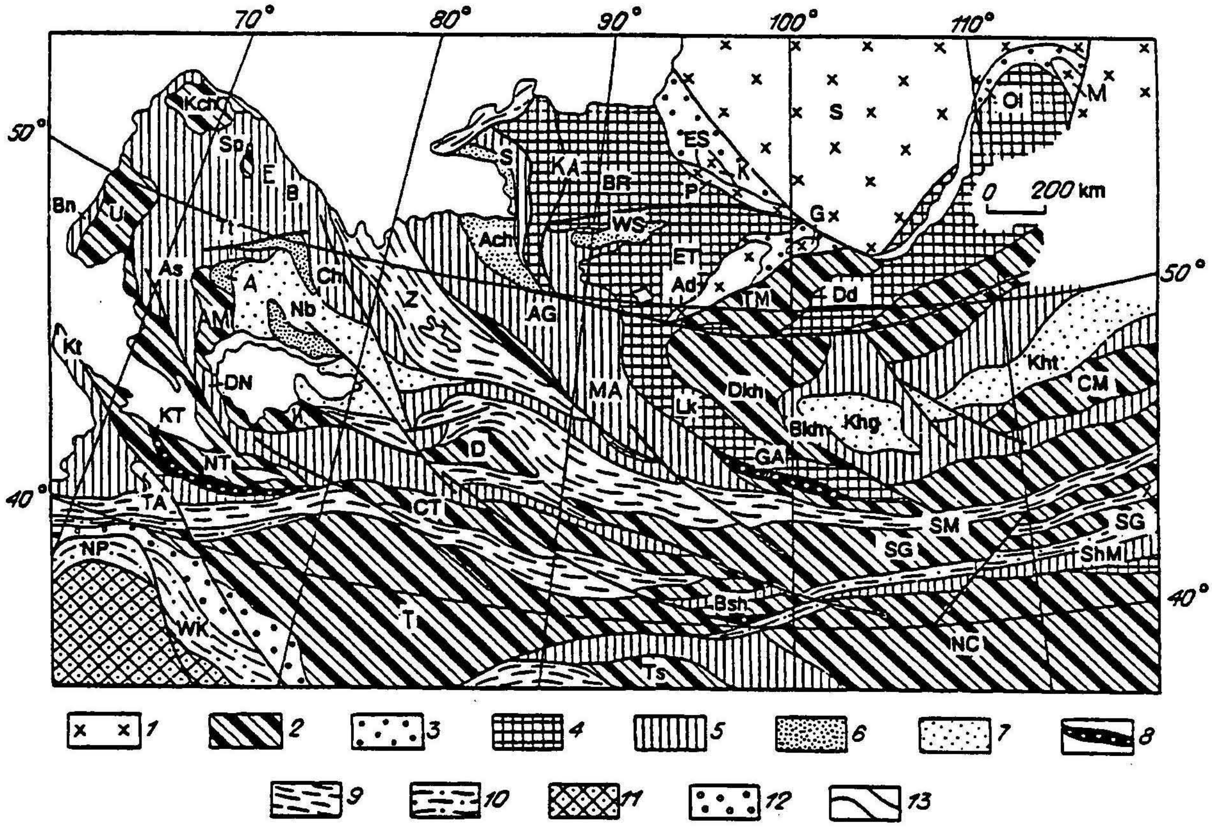


Figure 36 Tectonic scheme of the Central-Asian Fold Belt, after Didenko et al. (1994, fig.1). 1,2 = platforms and microcontinents; 1 = Siberian groups (S = Siberian Platform; P = Protero-Sayan; K = Kan; G = Gargan, and M = Muya "blocks"), 2 = of Gondwanan origin (T = Tarim and NC = North Chinese platforms; Kch = Kokchetav; U = Ulutau; AM = Aktau-Mointi; I = Ili; NT = North Tien-Shan; CT = Central Tien-Shan; D = Junggar; TM = Tuvino-Mongolian; Dkh = Dzabkhan; CM = Central Mongolian; SG = South Gobi; TS = Qaidam massifs); 3-5 = mosaic (accretion) fold systems: 3 = Late Riphean (ES = East Sayan, Ol = Olokit zone); 4 = Salair (KA = Kuznetsk Alatau, BR = Batenev Ridge; WS = West Sayan; ET = East Tuvinian; Ad = Agardag; Dd = Dzhida; Lk = Lake zones); 5 = Caledonian (Bn = Baikonur; Kt = Karatau; DN = Dzhalair-Naiman; As = Atasui; Tt = Tekturmas; Sp = Stepnyak; E = Erementau; B = Boshchekul; Ch = Chingiz zones; S = Salair; AG = Gorny Altai; MA = Mongolian Altai; Bkh = Bayan-Khongor; Bsh = Beishan; ShM = Shar-Muren); 6,7 = residual or overlapped troughs: 6 = Caledonian (A = Agadyr; ACh = Anui-Cuya); 7 = Variscian (NB = near-Balkhash; Khg = Khangai; Kht = Khentei); 8-11 = linear (collision) fold belts and sutures: 8 = Caledonian (KT = Khirghiz-Terskei; GA = Gobi-Altai); 9 = Variscan (TA = Turkestano-Alai; Z = Zaisan; SM = South Mongolian; Kh = Khegestan); 10 = Indo-Sinian and Late Variscan (SL = Solonker-Linxi; WK = West Kunlun; NP = Northern Pamir); 11 = Kimmerian; 12 = Pre-Kunlun trough; 13 = largest faults.

Ordovician, and (ii) development of the Palaeotethys (I and II) in several phases from Ordovician to Permian. In the Late Riphean reconstruction, the Siberian craton and northeastern Gondwana are separated by the Palaeoasian Ocean, with fragments of an oceanic nature along the east-facing margin of Siberia and numerous Gondwanan fragments positioned along northeastern Gondwana (Fig.37A). These are, on the inboard side, and from northern Greater Australia toward northern Greater India: North China, Tibet-Qaidam, Tarim, Ulutaum, Syrdaria-Karakum, South China, and outboard: Central Mongolia,

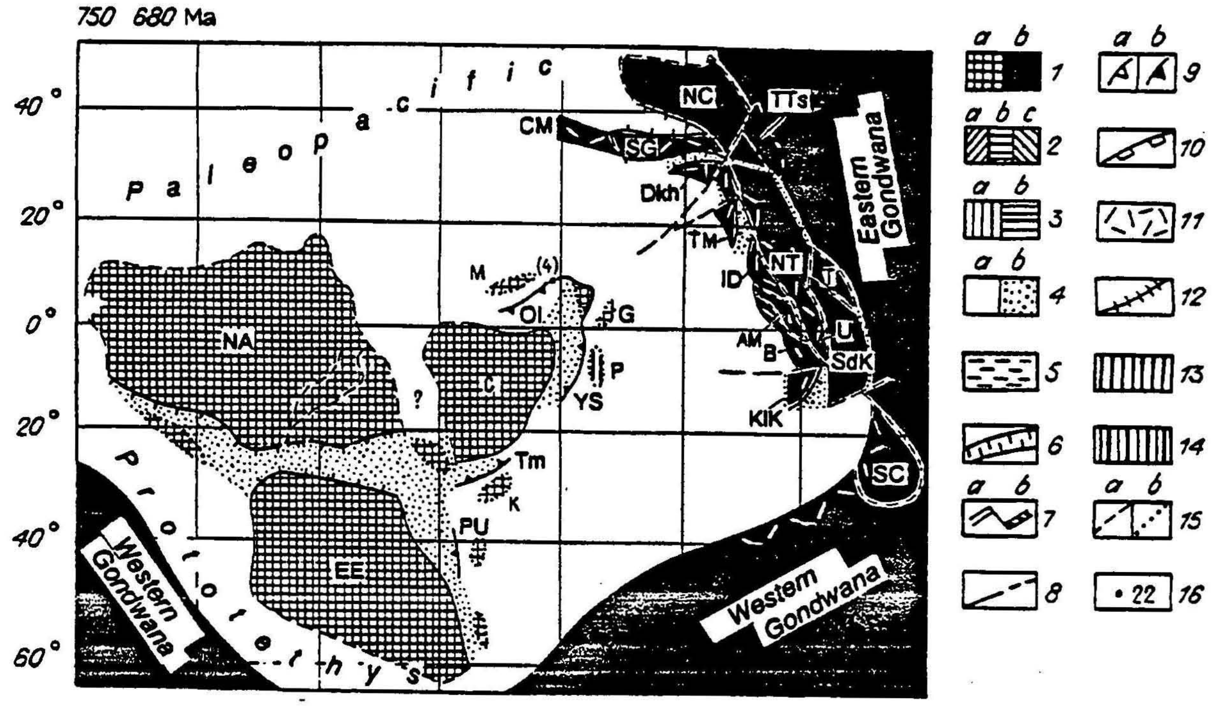


Figure 37A: Geodynamic reconstruction of the Palaeoasian Ocean in the Late Riphean, after Didenko et al. (1994, fig.2). Legend: 1 = Riphean continents, microcontinents and blocks of the Baltic-Siberian (a) and Gondwana (b) blocks, 2 = accretion zones originating in the Late Riphean (a), at the Middle-Late Cambrian (b) and Middle-Late Ordovician (c) borders, 3 = continental massifs formed in the Early Devonian (a) and Late Palaeozoic (b), 4 = basins with oceanic (a) and intermediate (b) crust, 5 = residual and overlapped flyschoid troughs, 6 = rifting structures, 7 = strike of the spreading axes (a) and swarms of diabase dykes of vague genesis, 8 = transform faults and shears, 9 = island arc volcanics, extinct (a) and active (b) with subduction, 10 = marginal-continental gentle zones of subduction, 11 = terrestrial marginal volcanic belts, 12 = ophiolite sutures, 13 = blocks with unknown basement, 14 = folded zones that appeared at the Devonian-Carboniferous boundary, 15 = boundary of blocks with younger complexes. Gondwana blocks: NC = North China, TT = Tibet-Qaidam, T = Tarim, SdK = Syrdaria-Karakum, SC = South China, CM = Central Mongolian, SG = Southern Gobi, Dkh = Dzabkhan, TM = Tuvino-Mongolian, ID = Ili-Junggar, NT = North Tien Shan, AM = Aktau-Mointin, U = Ulutau, B = Boschekul, KIK = Kulunda-Kokchetav; Palaeocontinents: S = Siberia, NA = North America, EE = Baltic (East European); Siberian blocks: M = Muya, G = Gargan, K = Kar, p = Protero-Sayan; Volcanic arcs: YS = Yenisei-Sayan, Tm = Taimyr, PU = Polar-Uralian.

Southern Gobi, Dzabkhan, Tuvo-Mongolia, North Tien Shan, Ill-Junggar, Aktau-Mointin, Boshchekul, Kulunda-Kokchetav. A remarkable aspect of Didenko's reconstructions is the exclusively westward journey that these fragments all embark on after breaking away from northeastern Gondwana. This occurs as early as Vendian to early Early Cambrian, simultaneously with accretion of the oceanic fragments fringing Siberia (Didenko et al.,1994: fig.3, Fig.37B). Westward movement of Gondwanan fragments continues with closure of the Palaeoasian Ocean in the Late Ordovician (Didenko et al.,1994: figs 4-6, Fig.37C-E). This represents the end of the Caledonian accretion phase. Cathaysian fragments such as the Altai-Sayan, North Tien Shan and notably the Sino-Korean block (North China) have then amalgamated. The Palaeotethys I starts opening up, particularly during the Late Silurian-Early Devonian,

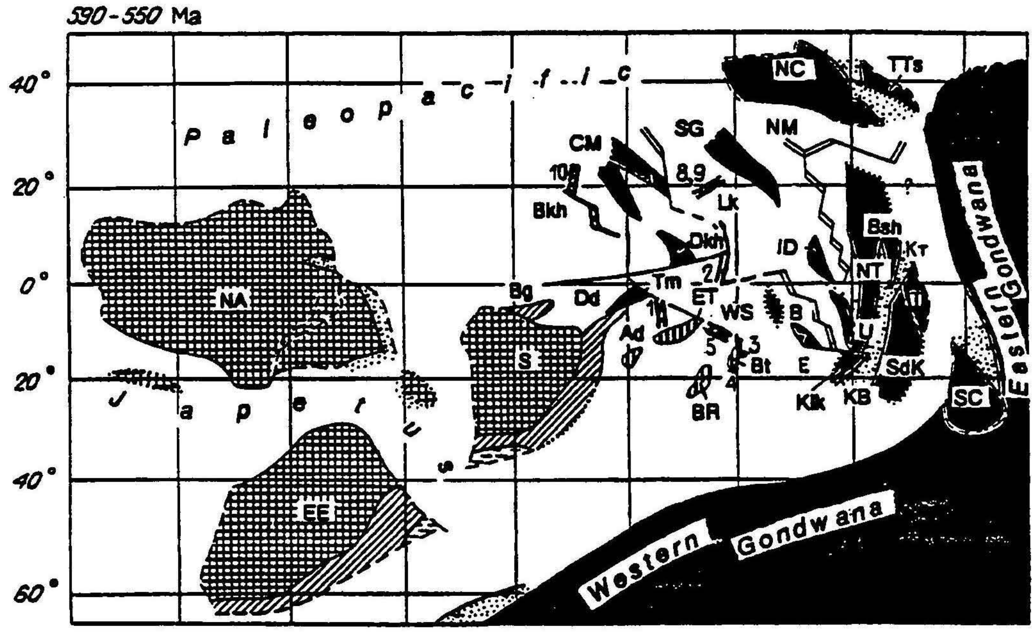


Figure 37B: Geodynamic reconstruction of the Palaeoasian Ocean in the Late Vendian-early Early Cambrian, after Didenko et al. (1994, fig.3). Symbols as per Figure 37A. The letters indicate oceanic basins and troughs: NM=Nei-Mongolian, LK=Lake Zone; Bkh=Bayan-Khongor; Dd=Dzhida; Ad=Agardag; WS=West Sayan; E=Erementau; KB=Karatau-Baikonur; Kt=Kurugtag; B=Boshchekul volcanic arc; microcontinents (massifs and blocks): Bg=Barguzin; ET=East-Tuvinian; Bt=Baratal; BR=Batenev Ridge; Bsh=Beishan. For the remainder of the massifs and palaeocontinents see notation in Figure 37A.

reaches maximum width during the Early Devonian (Didenko et al.,1994: fig.7, Fig.37F) and closes locally during the Early to middle Carboniferous (Didenko et al.,1994: fig.8, Fig.37G); in the east with accretion of Cathaysia and in the west with accretion of Kazakhstan. Simultaneously, Palaeotethys II started opening. Part of it closed very soon in the middle Carboniferous with accretion of the Tarim and Tadzhik blocks, but other parts closed no earlier than the Middle Triassic with accretion of the Sino-Korean block (Didenko et al.,1994: fig.9, Fig.37H).

In another leading paper Mossakovsky et al. (1994) developed a geodynamic scenario for evolution of the Central Asian Fold Belt that is quite similar to the scenario developed by Didenko et al. (1994). This is not surprising as the papers share three authors. There is, however, some noteworthy difference in detail. Mossakovsky admits that the relative positions of the major blocks - eastern Gondwana, Siberia, Baltica, North China and South China - are taken directly from Scotese and McKerrow (1991). Reconstruction of the Gondwanan fragments on Gondwana's northeastern margin is quite similar to Didenko et al., apart from a position of South China much closer to North China. South China again seems the only fragment to remain close to Gondwana, but has separated by the Early to Middle Devonian. Mossakovsky et al. stress the middle-Late Carboniferous as the epoch of one of the largest structural organisations and coalescence of crustal material. Palaeotethys I was closed, the last remnants

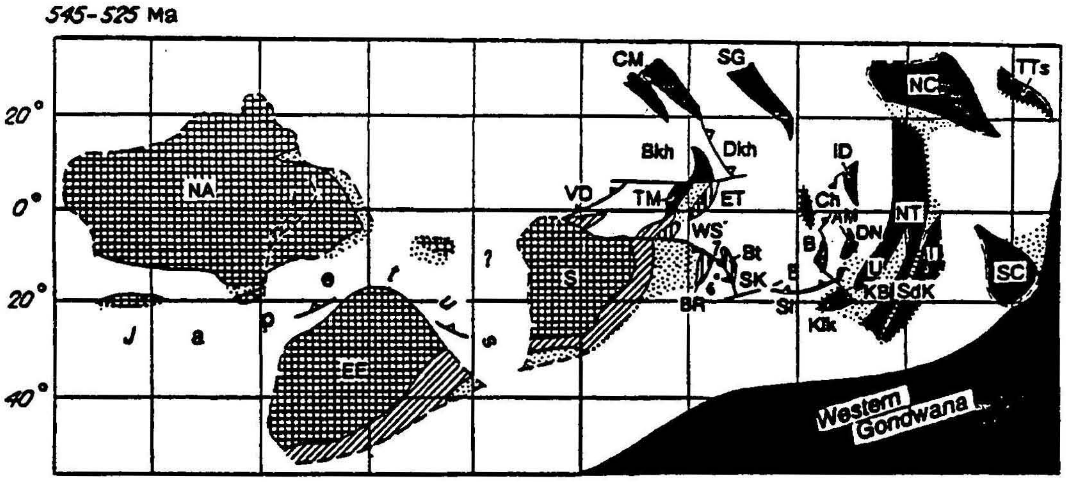


Figure 37C Geodynamic reconstruction of the Palaeoasian Ocean in the late Early-early Middle Cambrian, after Didenko et al. (1994, fig.4). The symbols follow Figure 37A. The letters indicate the volcanic arcs: VD = Vitim-Dzhida; DKh = Daribi-Kharkhirin; ET = East-Tuvinian; WS = West-Sayan; SK = Salair-Kuznetsk; Sl = Seletin; B = Boshchekul; Ch = Chingiz; basins: DN = Dzhalair-Naiman. For the other basins and troughs as well as continental massifs see notation in Figures 37A,B.

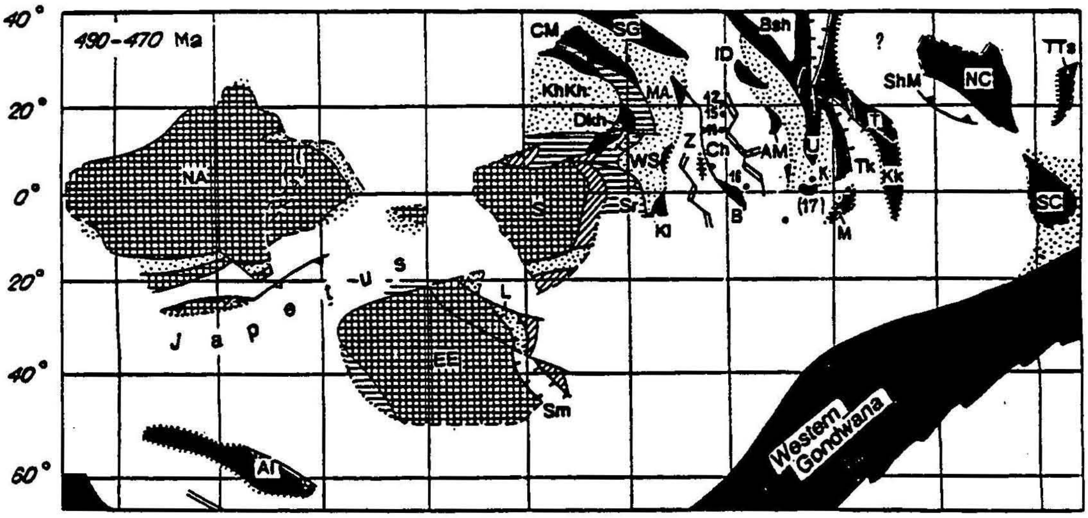


Figure 37D Geodynamic reconstruction of the Palaeoasian Ocean in the late Early Ordovician, after Didenko et al. (1994, fig.5). The symbols follow Figure 37A. The letters indicate the volcanic arcs: Sr = Salair; B = Boshchekul; Ch = Chingiz; ShM = Shar-Muren; basins and troughs: KhKh = Khangai-Khantei; MA = Mongolian-Altaian; WS = West-Sayan; Z = Zaisan; DN = Dzhalair-Naiman; Bsh = Beishan; Tk = Turkestan; L = Lemvin; Sm = Skmara; massifs: Kl = Kulunda; K = Kokchetav; M = Mugodzhary; Kk = Kara-Kum; Al = Avalon. For the remainder of the continental massifs see notation in Figure 37A.

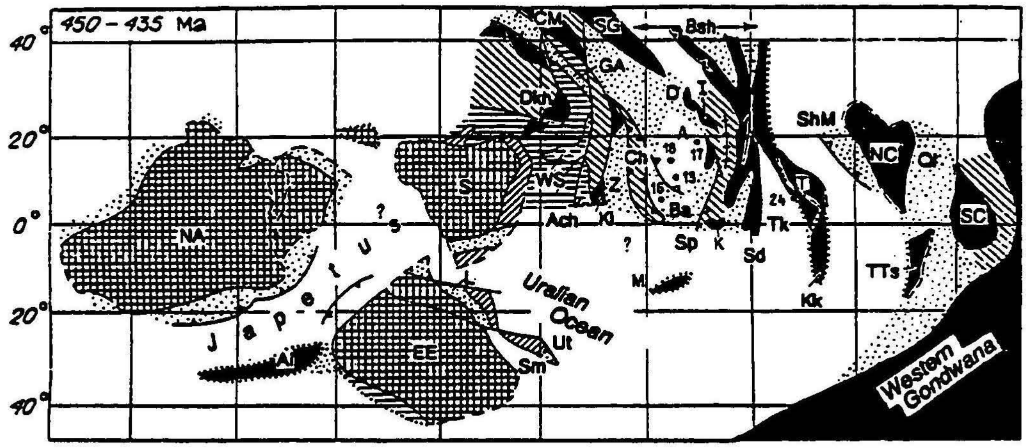


Figure 37E Geodynamic reconstruction of the Palaeoasian Ocean in the Late Ordovician, after Didenko et al. (1994, fig.6). The symbols follow Figure 37A. The letters indicate basins and troughs: GA= Gobi-Altai; WS=West Sayan; ACh=Anui-Chuya; Z=Zaisan; A=Agadyr; Bsh=Beishan; Tk=Turkestan; QI=Qinlin; Sm=Sakmara; L=Lemvinsk; volcanic arcs: Ch=Chingiz; BA=Baidaulet-Akbastau; Sp=Stepnyak; SHM=Shar-Muren; Ut=Uraltau (Guberlin); continents and microcontinents: NA=North America; Al=Avalon; EE=East-European; S=Siberian; Kl=Kulunda; Dkh=Dzabkhan; CM=Central-Mongolian; SD=South-Gobi; D=Junggar; I=Ili; NC=North-Chinese; SC=South-Chinese; TTs=Tibet-Qaidam; Kk=Kara Kum; T=Tarim; Sd=Syr-Daria; K=Kokchetav; M=Mugodzhary.

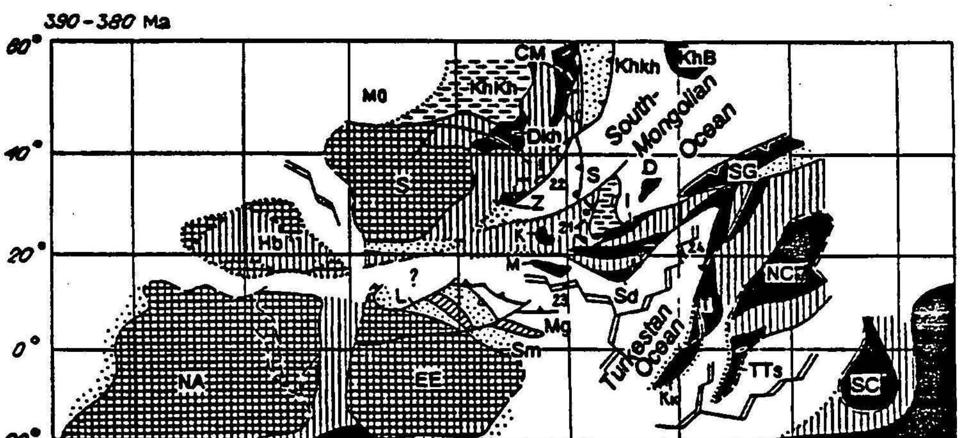


Figure 37F Geodynamic reconstruction of the Palaeoasian Ocean in the late Early-early Middle Devonian, after Didenko et al. (1994, fig.7). The symbols follow Figure 37A. The letters indicate the basins: MO=Okhotsk-Mongolian; KhKh=Khangai-Khentei; Z=Zaisan; volcanic arcs: KhKh=Khairkhan; S=Saur; Mg=Magnitogorsk; massifs: KhB=Khingano-Bureay; Hb=Hyperborean; For the remainder of the notations see Figure 37E.

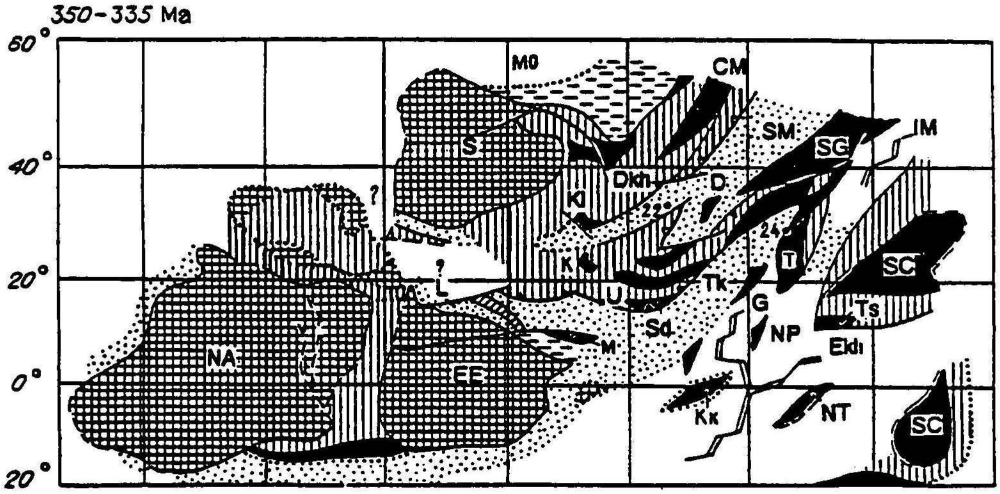


Figure 37G Geodynamic reconstruction of the Palaeotethys II in the early Early Carboniferous, after Didenko et al. (1994, fig.8). The symbols follow Figure 37A. The letters indicate the basins: MO=Okhotsk-Mongolian; SM=South-Mongolian; Tk=Turkestan; G=Gissar; NP=North Pamir; EKl=East Kunlun; IM=Inner Mongolian; massifs: Ts=Qaidam; NT=North-Tibet. For the remainder of the notations see Figure 37E.

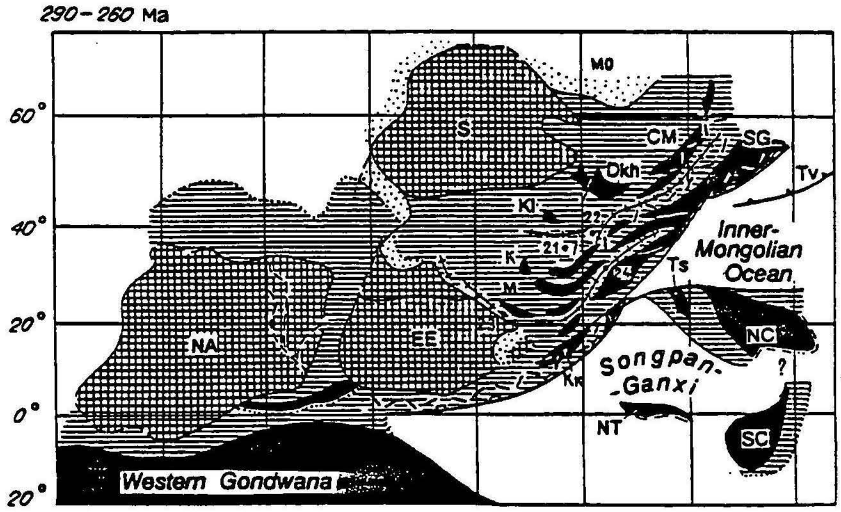


Figure 37H Geodynamic reconstruction of the Palaeotethys II in the Early Permian, after Didenko et al. (1994, fig.9). The symbols follow Figure 37A. Tv=Tavan volcanic arc. For the remainder of the notations see Figure 37E.

of the Palaeoasian Ocean were closed, and surprisingly Palaeotethys II opened at the same time or had done so already in the Late Devonian, with opening of the Northern Pamir, Gissar and Inner Mongolian oceanic basins. This is a situation reminiscent of the Amadeus Basin-Canning Basin during the Late Devonian and Carboniferous with compression in the Amadeus Basin and extension in the Canning Basin. Was there at that time, perhaps, a coherence between these now far apart regional structures? Another, perhaps, personal interest stressed by Mossakovsky et al. is the difficulty in linking spreading and subduction cycles. Throughout the evolution of the Palaeoasian and Palaeotethys I and II Oceans, there were shortlived bursts of spreading and long periods of subduction. This seems in conflict with the principles of plate tectonics and Mossakovsky et al. suggest as an alternative their own model of tectonic stratification of the lithosphere.

Geodynamic Evolution of China

Geological knowledge of China has increased vastly in the past fifteen years. There is now a considerable base of biostratigraphic, geochronologic, tectonic, lithostratigraphic, and other field data relevant to movements of the various Chinese cratons, both internally and with respect to the Siberian craton. Yet, no clear evolutionary patterns have emerged. This mainly reflects the prolonged nature and complexity of repeated interactions, but is also partly due to the relatively recent introduction of modern plate tectonic concepts in Chinese geological thinking. Understandably, but unfortunately, no synthesis on the geodynamic evolution of China has been produced so far which can be regarded as comprehensive, authoritative and non-controversial. Leading Chinese literature seems more preoccupied with hierarchical classification of tectonic structures than with grand geodynamic schemes of the standing of Zonenshain et al.'s (1990) magnificent work on the evolution of the former USSR. Likewise, no integrated biostratigraphic and lithostratigraphic synthesis regarding the original location of Chinese cratonic blocks within Gondwana has been produced, that is any more informative than the works produced by the authors so far referenced.

For the purpose of this review, a brief extract is presented from a recent outline of the tectonic evolution of China, which was compiled as background information for the 30th International Geological Congress in Beijing (Hongzhen Wang and Xuangxue Mo,1996). References to other relevant studies and views are incorporated. This extract concentrates mainly on the timings of accretion because these pose minimal constraints on the timings of dispersion of individual blocks from Gondwana. The outline provides little or no constraint on the original location of these blocks within Gondwana.

China is made up of three cratons of surmised Gondwanan origin, Sino-Korea or North China, Yangtze or South China, and Tarim (Fig.38). These blocks and their interstitial fold belts were finally welded together and to the Siberian craton in the Late Triassic during the pervasive Indosinian Orogeny. Other massifs of Gondwanan origin that accreted or amalgamated successively in post-Indosinian times to Laurasia are now aligned along the northern and northeastern border of the Indian shield (Fig.38; Hongzhen Wang and Xuangxue Mo,1996: fig.1, Fig.39). The Tarim Domain is taken to include the Tarim platform and the surrounding Palaeozoic fold belts of the Kun Lun and Tien Shan. The Sino-Korean Domain may possibly be related to the Tarim Domain through the Qaidam block, although Sino-Korea and Kazakhstan probably belonged to separate faunal provinces during the Palaeozoic. The Korean platform, at least as far south as the Ocheon zone, belongs to the Sino-Korea Domain. The Yangtze Domain probably included the North Qiangtang, Qamdo and Lincang-Simao blocks that became

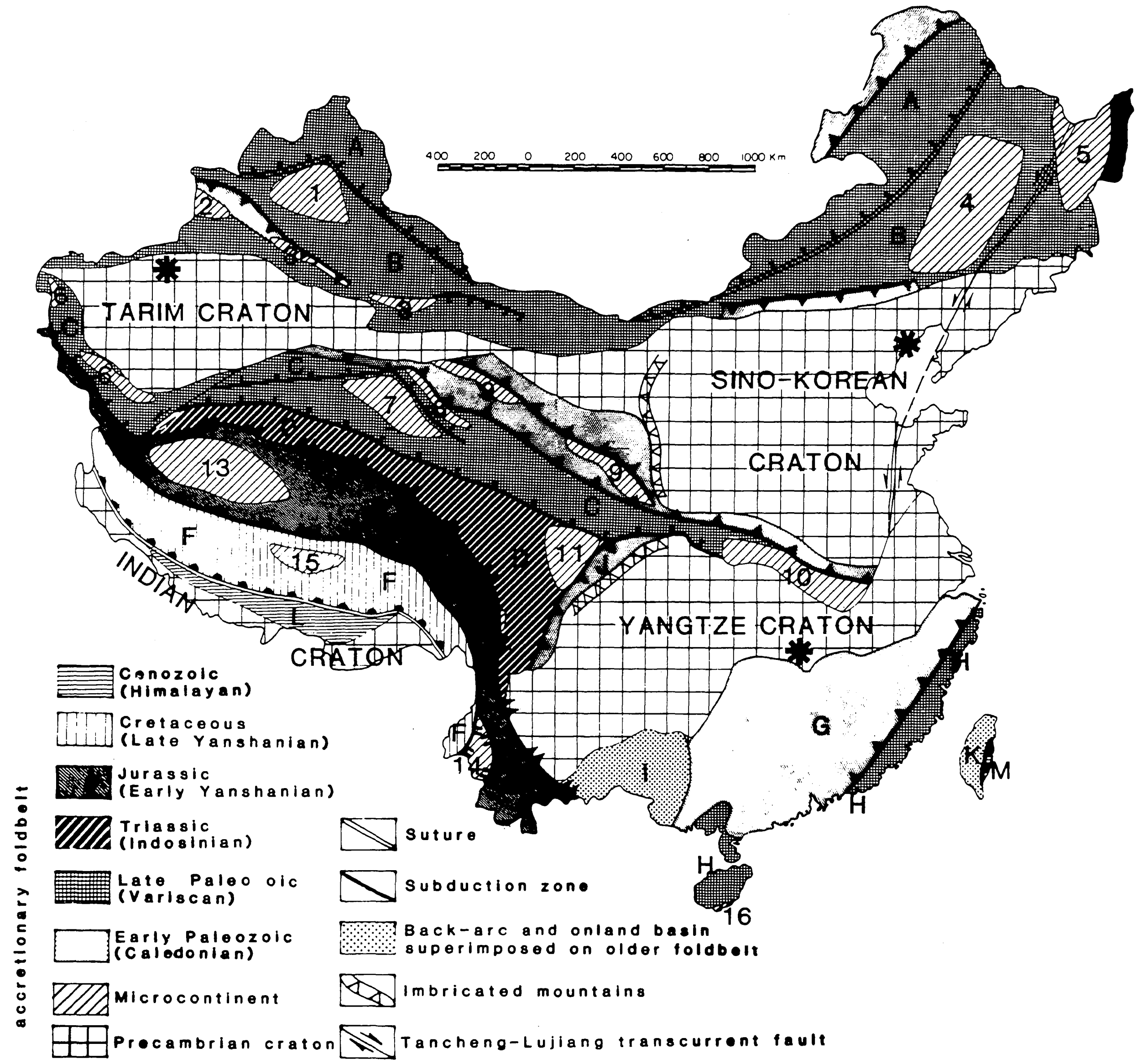
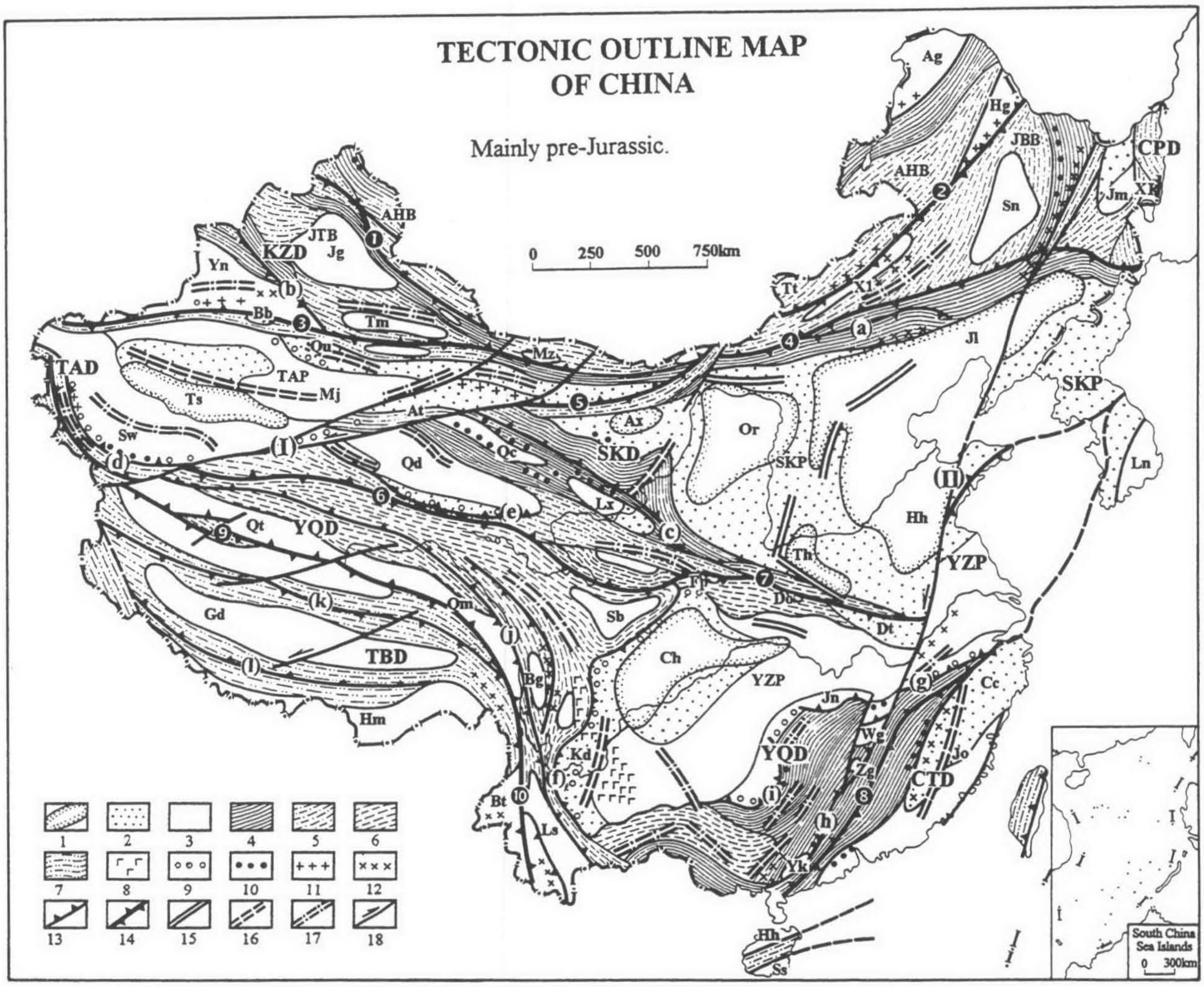


Figure 38 [above] Overview of plate tectonic elements of China, after Zhang et al. (1984, fig.1).

Figure 39 [opposite page] Tectonic outline map of China, after Hongzhen Wang and Xuanxue Mo (1996, fig.1).

detached in the Late Palaeozoic. A confusing and controversional aspect of Wang and Mo's study is the definition of a Cathaysian Domain that does not include the Yangtze Domain!

Three main tectonic stages are identified during the Phanerozoic, i.e. Caledonian, Hercynian and Indosinian, but the latter two may not be identifiable as separate events in South China. An extensional



1 *Continental nuclei, 2800 Ma (Ar_3)*
2 *Protoplatforms, 1800 Ma (Pt_1)*
3 *Platform and massifs 800 Ma (Pt_3)*
4 *Caledonides*
5 *Hercynides*
6 *Indosinides*
7 *Yanshanides and Himalayaides*
8 *Permian basalts*
9 *Jinningian (Pt_{2-3}) granitic zones (J)*
10 *Caledonian (Pz_1) granitic zones (C)*
11 *Hercynian (Pz_2) granitic zones (H)*
12 *Hercynian–Indosinian (P-T) granitic zones*
13 *Accretional crustal consumption zones (AZ)*
14 *Convergent crustal consumption zones (CZ)*
15 *Pt_{2-3} aulacogens and rifts*
16 *Z–O aulacogens*
17 *D–T aulacogens*
18 *Strike-slip faults, mostly post-Indosinian.*

Tectonic units:

AHB *Altai–Hingan Belt:*
Ag *Arguna Massif*
Hg *northern Hingan Massif;*
Tt *Tuotuoshan Massif*
JBB *Jamus–Bureya Belt:*
Jm *Jamus Massif*
Sn *Songnen Massif*
Xl *Xilinhot Massif.*
KZD *Kazakhstan Domain:*
Yn *Yinnin Massif*
Jg *Junggar Massif*
Tm *Turpan–Hami Massif.*
TAD *Tarim Domain:*
TAP *Tarim Platform:*
Ts *Central Tarrim Nucleus*
Sw *South-western Region*
Mj *Manjyar Region*
Qu *Quruktagh Region*
At *Altun Region*
Bb *Bayanbluk Massif*
Mz *Mazongshan Massif.*
SKD *Sino-Korea Domain:*
SKP *Sino-Korea Platform:*
Or *Ordos Nucleus*
Jl *Jiliao Nucleus*
Hh *Hehuai Nucleus*
Th *Taihua Nucleus*
Ax *Alxa Nucleus*
Qc *Central Qilian Massif*
Lx *Longxi Massif*
Qd *Qaidam Massif.*
YQD *Yangtze–Qiangtang Domain:*
YZP *Yangtze Platform:*
Ch *Chuanzhong Nucleus*
Kd *Kangdian Region*
Kd *Jiangnan Region*
Dt *Dabie–Tongbe Massif*
Do *Douling Massif*
Fp *Fuping Massif*
Qt *Qiangtang Massif*
Qm *Qamdo Massif*
Bg *Batang Massif*
Sb *Songpan–Bikou Massif*
Ls *Lincang–Simao Massif*
Wg *Wugong Massif*
Zg *Zhuguang Massif*
Yk *Yunkai Massif.*
CTD *Cathaysian Domain:*
Cc *Chencai Massif*
Jo *Jianou Massif*
Ln *Lingnan Massif*
Hn *Hainan Massif*
Ss *South China Sea Massif.*
TBD *Tibet–Burma Domain:*
Gd *Gangdise Massif*
Hm *Himalaya Massif*
Bt *Baoshan–Tengchong Massif.*
CPD *Circum-Pacific Domain:*
Xk *Xingkai Massif.*

CZ Convergent zones:

1 *EKCZ Ertix–Kalameili (H)*
2 *HGCZ Heganshan (H)*
3 *TMCZ South Tianshan –Mazongshan (H)*
4 *SLCZ Soulun–Linxi (H)*
5 *EUCZ Enger Usu (H)*
6 *XMCZ Xiugou–Maqin (I)*
7 *FTCZ Fengxian –Tongcheng (I)*
8 *SSCZ Shaoxing–Shaoguan (C)*
9 *LSCZ Longmucuo–Shuanghu (I)*
10 *MCZ Changning–Menglian (I).*

AZ Accretional zones:

(a) *OSAZ Ondor Sum (C)*
(b) *AXAZ Aibihu–Xingxingxia (H)*
(c) *QQAZ North Qilian–North Qinling (C)*
(d) *KWAZ West Kunlun (J)*
(e) *KEAZ East Kunlun (J)*
(f) *LHAZ Longmenshan–Honghe (J)*
(g) *SCAZ Shexian–Changsha (J)*
(h) *WYAZ Wugong–Yunkai (C)*
(i) *SBAZ Sibao (J)*
(j) *JTAZ Jinshajiang–Tengtiaohe (I)*
(k) *BNAZ Banggong–Nujiang (YH)*
(l) *YZAZ Yarlung Zangbo (YH).*

(J Jinningian; C Caledonian; H Hercynian; I Indosinian; YH Yanshanian–Himalayan)

SF Strike-slip faults:

(I) *Altun;*
(II) *Tanlu.*

regime predominated during the Caledonian stage in the Tarim and Sino-Korean Domains, which is in agreement with the Russian syntheses discussed above. Oceanic basins started to shrink in the Late Ordovician, and closed in the Late Silurian. The Sino-Korean Domain had a passive northern margin during the Devonian part of the Hercynian stage and collided locally with the Siberia-Mongolian Domain in the Early Carboniferous, and in full in the Late Permian. The Kazakhstan, Tarim and Altai Domains also welded during this Late Hercynian event. This marked the final disappearance of the northern Palasian Ocean (Palaeoasian) and the emergence of Palaeotethys as a major southern ocean. The Yangtze Domain and Sino-Korean Domain were in near proximity from the Devonian onwards for the duration of the Hercynian and Indosinian stages, with final welding during the Late Triassic Indosinian Orogeny. The Yangtze Domain and the Cathaysian Domain (read Indochina) became united at the end of the Silurian, but extensional conditions prevailed in the Devonian with rifting of the northern Qiangtang Domain, with full separation by Permian time. The Palaeotethys finally closed during the Late Triassic Indosinian Orogeny with final welding of the Sino-Korean Platform and the Yangtze Platform. The Indosinian Orogeny was a major diastrophistic event, largely overprinting the effects of the Hercynian Orogeny. Hongzhen and Mo conclude with the observation that there is a comparative lack of ancient large oceans and deep oceanic basins prior to the Mesozoic in contrast to what would be expected from plate tectonic reconstructions, and suggest that earth expansion may have occurred.

The effects of the Indosinian Orogeny are widespread and are particularly notable in the Qinling-Dabie Shan, where the Late Triassic final welding of the North and South China blocks is dated radiometrically between 230 Ma and 210 Ma (Guowei et al.,1989; Ames et al.,1993; Yin Hongfu,1994; Nie Shangyou et al.,1994; Zhang et al.,1995; Ames et al.,1996). Despite this tectonic overprinting there is convincing evidence for collision of the North and South China blocks during the Hercynian. It is, perhaps, a result of this complexity that time constraints for this collision vary considerably i.e. Late Ordovician to Early Silurian (Xue et al.,1996), Silurian-Devonian (Gao et al.,1995), pre-Devonian (Chang et al.,1994; Yin Hongfu,1994), Devonian (Wenpu,1989), Late Devonian and Carboniferous (Zhang et al.,1995), pre-Carboniferous (Fuquan,1989) and pre-Late Carboniferous (Guang et al.,1994). Likewise the final closure of the Palaeoasian Ocean with welding of surmised Gondwanan fragments to the Siberian craton-Altaids complex is an Hercynian event of some protracted duration i.e. Middle Carboniferous welding of Kazakhstan and Tarim with Siberia (Yabukchuk and Degtyarev,1994), Late Devonian-Early Carboniferous to Late Carboniferous-Early Permian welding across the Tien Shan (Feng et al.,1989; Allan et al.,1992; Yin Hongfu,1994; Carroll et al.,1995) and pre-Late Devonian (Yunping and Kedong,1989), pre-Late Palaeozoic (Chang et al.,1994), or Early Permian (Yin Hongfu,1994) welding of the Sino-Korean block to southern Laurasia. Such a protracted, dual collision process is also well-established for the South China and Indochina blocks with initial suturing during the Carboniferous along the Song Ma suture and final suturing during the Late Triassic along the Song Da suture (e.g. Yin Hongfu,1994; Metcalfe,1988).

Gondwana Terranes: North American Cordillera, NE and N Russia

Basic principles of terrane analysis are described in seminal papers by Coney et al. (1980) and Jones et al. (1983). A very readable description of tectonostratigraphic terranes in the North American Cordillera is presented in Saleeby (1983) and a detailed and up-to-date evolutionary account is given in Speed (1994). Monger (1991) details the evolution of the terrane concept for the Canadian region of the Cordillera, and Howell et al. (1985) describe North American and northeast Russian terranes in a

Figure 40 Major tectonic elements of the Arctic, after Churkin (1972, fig.2).

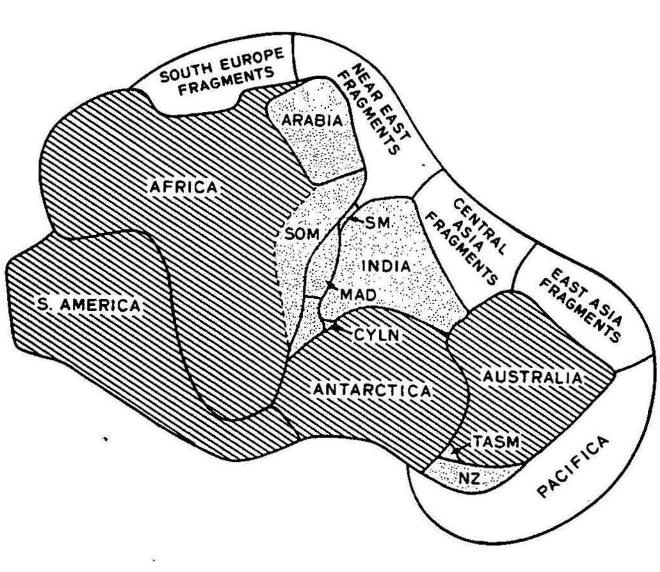


Figure 41 Speculative reconstruction of the Pacifica continent as part of Gondwana, after Nur and Ben-Avraham (1983, fig.7).

Circum-Pacific setting. Detailed accounts of northeastern Russian terranes and their evolution are presented in Fujita and Newberry (1983) and Zonenshain et al. (1990).

It is common in Russian and American literature to confine descriptions of the Panthalassa-born terranes around the Pacific rim to either those now residing outboard of the North American Shield or outboard of the Verkhoyansk Fold Belt. Yet, they probably share a common origin. The Japanese Kurosewaga terrane, not discussed here, and probably also the (North) Taimyr terrane of northern Siberia (Fig. 23B; Churkin,1972: fig.2, Fig.40) may belong to this province. Churkin and others (Churkin,1972,1983; Fujita and Newberry,1983; Churkin et al.,1985) pointed out in various papers that the Kolyma-Chukotka region in northeastern Russia and the Alaskan region of the North American Cordillera share a common evolution, and the concept of a common origin of Pacific-rimming terranes as part of a hypothetical Pacifica continent was strongly advocated in a series of papers by Amos Nur and Zvi Ben-Avraham (1977,1978,1982,1983). Nur and Ben-Avraham built their argument for a Pacifica continent, which they thought was located along eastern Australia and northeastern Antarctica (Fig.41), on faunal and floral observations that date back to the early 1900's. These early studies stressed relationships between species and families in widely dispersed regions surrounding the Pacific (Nur and Ben-Avraham,1982: fig.1, Fig.42). The presence of distinctly Tethyan taxa in suspect terranes of the North America Cordillera has become well-documented (e.g. Stanley,1994), and the argument for a trans-Pacific origin of some of the major (super-)terranes, Wrangellia, Stikinia and Eastern Klamath, has been quantified by Belasky and Runnegar (1993,1994). Their argument is based on the diversity grade of Permian corals against the well-established trans-Pacific longitude dependency in diversity of modern corals. They concluded that the three superterranes were situated between 7000-3000 km to the west of the North American Pacific margin, and could establish a Permian westward movement for the Eastern Klamath terrane.

Figure 42 Sketch map of past, present and future allochthonous terranes, most of which are fragments of continents or have clear continental affinity, after Nur and Ben-Avraham (1982, fig.1; 1983, fig.6). Shaded areas indicate Mesozoic-Cenozoic orogenic belts. Allochthonous terranes within the belts are most likely parts of Gondwana which have migrated toward and collided with Europe, Southeast Asia and the Pacific margins.

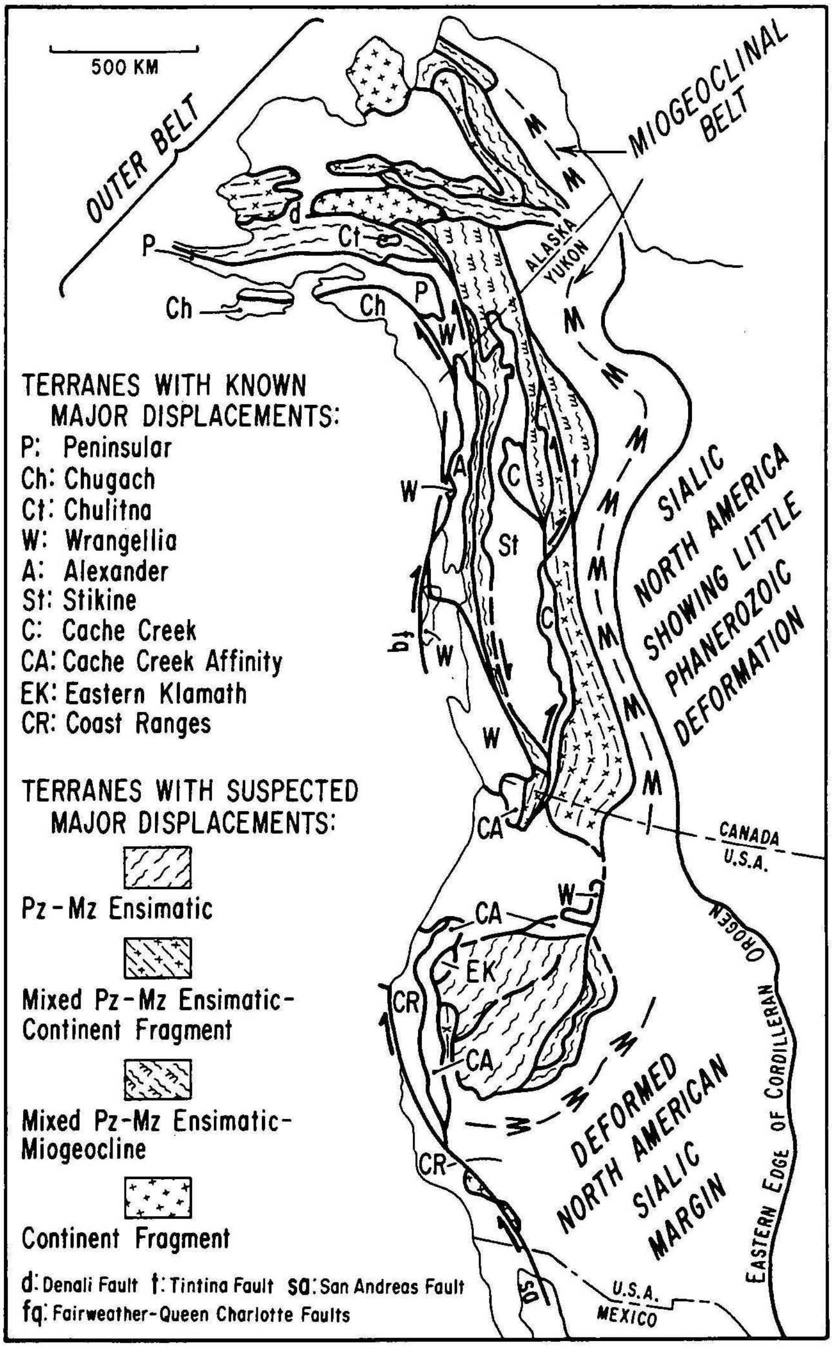


Figure 43 Schematic overview of tectonostratigraphic terranes in the North American Cordillera, after Saleeby (1983, fig.1).

North American Cordillera

The miogeosynclinal belt representing the western margin of the North American craton and the eastern margin of the Cordillera is made up of a sedimentary succession that has been fairly continuous since

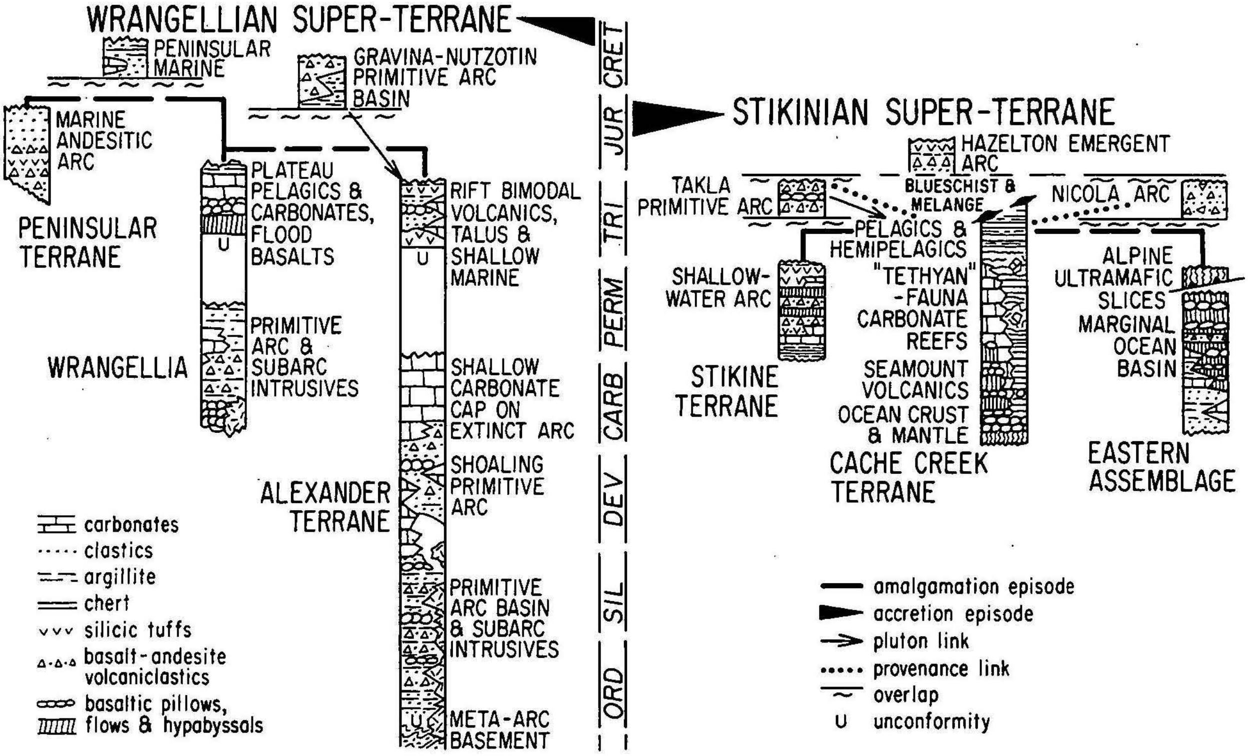


Figure 44 Diagram showing the petrotectonic, amalgamation, and accretion histories of the Wrangellian and Stikinian super-terranes of British Columbia and southern Alaska, after Saleeby (1983, fig.2).

the Late Proterozoic-Early Cambrian process of breakup of Rodinia and separation of the western North American craton from cratonic Australia. Stable miogeosynclinal conditions persisted throughout the Middle Palaeozoic until the arrival of the first terranes during the Mississipian and again in the Permo-Triassic. The Cordillera outboard of the miogeosynclinal belt (Saleeba,1983, fig.1, Fig.43), is entirely made up of terranes that often became boudinaged upon subsequent northward transport during the Mesozoic. The terranes can be grouped into two super-terranes, Wrangellia and Stikinia (Saleeby,1983), whose schematised tectonostratigraphic evolution is shown in Figure 44.

The Wrangellian super-terrane is made up of the Alexander, Wrangellia and Peninsular terranes. The Alexander terrane has the longest evolutionary history of all terranes in the Cordillera. It shows an Ordovician to Devonian basinal-arc sequence that evolved during the Devonian into a mixed arc-shallow carbonate sequence with cessation of arc activity in the Carboniferous. The adjacent Wrangellia terrane shows basinal-arc activity during the Carboniferous to Middle Permian. An Upper Permian-Lower Triassic hiatus is followed by an extensive succession of Late Triassic-earliest Jurassic shallow flood basalts that are capped by pelagic carbonates. The Wrangellia and Alexander terranes amalgamated during the Early to Middle Jurassic and accreted to the craton in middle to Late Cretaceous time.

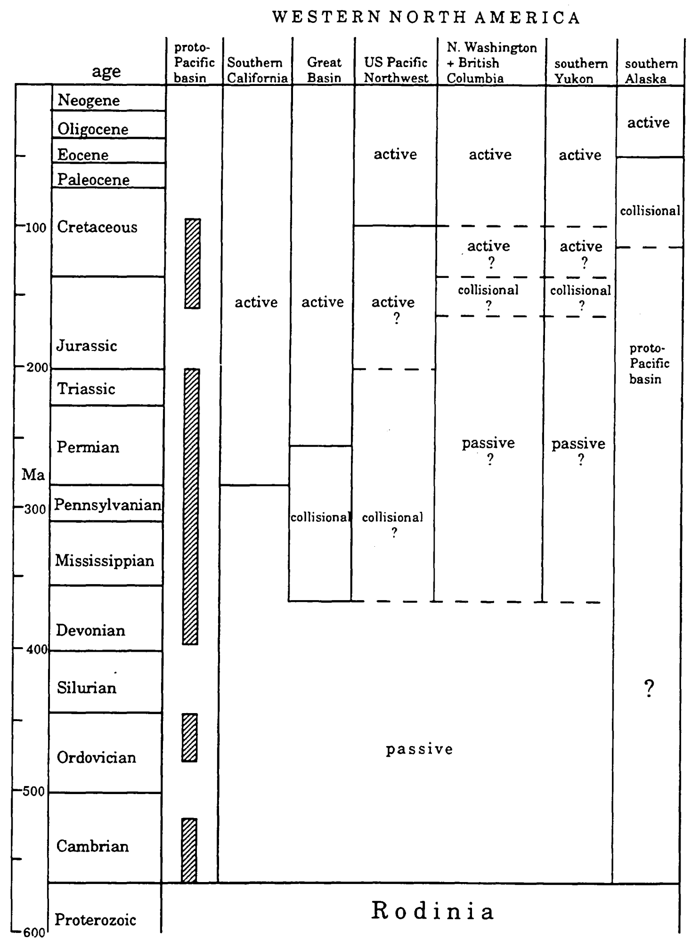


Figure 45 Successions of Phanerozoic margin types versus position in western North America and durations of tectonic activity in the proto-Pacific basins recognised in ophiolites and oceanic basalts in terranes, after Speed (1994, fig.21).

The Stikinia super-terrane is made up of the Stikine and Cache Creek terranes. The Stikine terrane is the largest individual crustal fragment in the Cordillera. It shows an Upper Palaeozoic, shallow volcanic arc succession with a Permian Schwagerinid fusilinae fauna that is notably different from the Verbeekinid fusilinae fauna of the adjacent Cache Creek terrane, but similar to the fauna of the Eastern Klamath terrane of California. The Cache Creek terrane contains exotic elements characterised by a Carboniferous to Permian Verbeekinid fauna which is clearly of Tethyan affinity. It is this affinity that led biogeographers as long ago as early this century, to the original concept of trans-Pacific connections. The succession is capped by a blueschist-melange sequence that is related to Middle to Late Triassic accretion of the Stikine and Cache terranes onto a more eastern assemblage.

Speed (1994) presents a detailed overview of the south to north evolution of collisional activity along the Cordillera from California to northern Alaska (Fig.45), lasting from Late Devonian to mid-Cretaceous. The

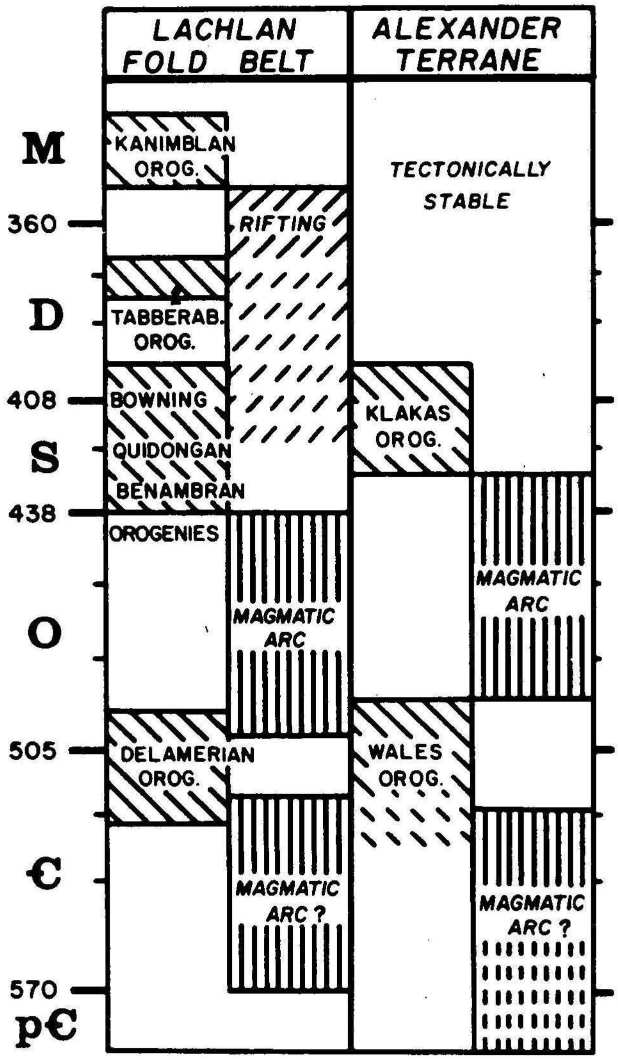


Figure 46 Comparison of the main tectonic phases and events in the Early Palaeozoic evolution of some regions of the Alexander terrane and the Lachlan Fold Belt, after Gehrels and Saleeby (1987,fig.7).

two earliest collisions, recognised from fragments that are now in a very internal position, occurred in the Great Basin region of the southern Cordillera: the Late Devonian to middle Carboniferous accretion of the Roberts Mountain terrane that could be related to the Antler Orogeny, and the Permian to Early Triassic accretion of the Golconda terrane (Speed,1979,1994). There is no evidence of such early collisional activity in more northern parts of the Cordillera, but such evidence could have been removed by tectonic shaving resulting from northward transport of accreted terranes. Convincing palaeomagnetic evidence for large-scale northward transport of terranes has been presented in many studies (e.g. Packer and Stone,1972; Thrupp and Coe,1986; Hagstrum et al.,1987), with the most conclusive early evidence presented by Hillhouse (1977). He showed from convincing palaeomagnetic evidence that the

Triassic flood basalt successions of the boudinaged Wrangellia terrane were formed in a narrow latitudinal band close to the equator, in good agreement with faunal evidence for such a low latitudinal origin. An equatorial origin for these terranes is far to the south of their present positions which are spread over about 25 degrees of latitude along the Canadian coast. The considerable amount of palaeomagnetic evidence for large-scale and prolonged northward transport, however, has not been universally accepted by palaeomagnetists and other workers. More complex schemes of north-to-south followed by south-to-north movements of smaller magnitude have been proposed by some authors (e.g. Irving and Wynne,1991). These authors emphasised the difficulties of polarity interpretation of sub-horizontal magnetisations from such heavily tectonised terranes, leading to uncertainty in original north or south hemisphere location, and also problems with determination of the palaeohorizontal in igneous successions leading to questionable latitude determinations. The dispute on the magnitude and evolution of northward motions of Cordilleran terranes is by no means settled. It is, perhaps, illustrative of the complexity of the problems to be solved that recent results from the very authors that have cautioned against pitfalls of palaeomagnetic interpretations, have been questioned themselves on palaeomagnetic grounds (e.g. Wynne et al.,1995,1996; Irving et al.,1995; Monger and Price,1996).

In a thought-provoking paper that surprisingly has not been followed up with further test studies, Gehrels and Saleeby (1987) suggested, on the basis of tectonostratigraphic rather than faunal evidence, an original Early to Middle Palaeozoic association of the Alexander terrane with the east Australia-east Antarctica margin of Gondwana, and in particular with the Lachlan Fold Belt (Fig.46). They noted, followed by Coney (1990): that the Alexander terrane and the Lachlan Fold Belt evolved both in a magmatic arc environment during the Cambrian; were deformed during the Middle Cambrian-Early Ordovician (Delamarian Orogeny in south(eastern) Australia, Wales Orogeny in Alexander terrane); evolved in a basinal-arc environment during the Ordovician; and experienced a Silurian-Early Devonian orogenic episode (Benambran-Quidongan-Bowning orogenic events in the Lachlan Fold Belt, Klakas Orogeny in Alexander Terrane). The Middle Devonian to Lower Permian succession of the Alexander terrane developed in a tectonically stable environment apparently in near-equatorial palaeolatitudes as indicated by lithostratigraphic, faunal and palaeomagnetic data. There is apparently no evidence of the Middle Devonian Tabberaberan Orogeny or the mid-Carboniferous Kanimblan Orogeny in the Alexander terrane. The authors thus conclude an Early-Middle Devonian separation of the Alexander terrane and Late Palaeozoic drift across the palaeo-Pacific to a low southern location near South America during latest Palaeozoic-Triassic time. Evidence for a latest Permian(?)- Triassic rifting phase is then interpreted as Late Triassic initiation of large-scale northward transport along the North American Cordillera that continued until final accretion during the Late Cretaceous-Early Tertiary. It should be noted that the effects of the Tabberaberan Orogeny are not universally observed throughout the Lachlan Fold Belt, in contrast to the pervasive effects of the Kanimblan Orogeny. Thus, perhaps, a post-Tabberaberan separation but prior to the- Early to middle Carboniferous Kanimblan Orogeny, might have been a more appropriate suggestion. In any case the distinctly east-Tethyan affinity of the Early Permian coral faunas of the Stikinia and Wrangellia superterranes and the Eastern Klamath terrane (Belasky and Runnegar,1994) suggests that the Alexander terrane (and others?) remained at least till the Late Permian in a low-latitude western Pacific location. In contrast, Australia occupied south polar latitudes during the Permian. Thus, separation of the North American terranes must have occurred prior to the Visean-Namurian fast southward movement of Australia. Perhaps the "Pacifica" fragments remained behind together with the Cathaysian fragments in equatorial latitudes during middle Carboniferous reversal of Australia's northward movement into a high speed southward movement.

Gehrels and Saleeby's provocative suggestion is of fundamental importance for the origin of terranes that are now located in the North America Cordillera and perhaps also in northeastern Russia. Surprisingly this suggestion has not been followed up by palaeomagnetic and other workers in North America and Australia. A recent palaeomagnetic study by Bazard et al. (1995) on Lower Devonian redbeds of the Alexander terrane shows original palaeolatitudes that are comparable to southeastern Australia, although the authors prefer instead an original association with Baltica on rather weak palaeontological grounds. Hopefully, a suggested IGCP proposal, currently under development (Larry Harrington, pers.comm., 1996), will result in more active and more conclusive testing of Gehrels and Saleeby's suggestion.

Northeastern and Northern Russia

There are two groups of continental blocks in northeastern and northern Russia that can be related geodynamically, and probably also in terms of origin, to the collage of terranes in the North American Cordillera: the Omolon and Okhotsk blocks, and the East Chukotka and (North) Taimyr blocks (Fig. 23B, Zonenshain et al.,1990: figs 109,118, Figs 47,48).

The Omolon and Okhotsk blocks are now separated but are probably remnants of the same continental mass. The Omolon block forms the central block within the Verkhoyansk-Kolyma Belt, whereas the Okhotsk block bifurcates this belt in the south. The blocks have a sedimentary-volcanic cover starting with Vendian tillites, Cambrian carbonates, Ordovician conglomerates and red beds, and are overlain with a pronounced unconformity by Middle to Upper Devonian calc-alkaline volcanics. This succession has no equivalent on the Siberian craton, but its resemblance to northeastern Australia has been stressed (Zonenshain et al.,1990). Palaeomagnetic data have been interpreted to show that the blocks remained in low (northern) latitudes during the Late Devonian to Late Triassic-Early Jurassic and underwent fast and large-scale northward movement during the Jurassic. There is thus an obvious analogy with the geodynamic evolution of the Cordilleran terranes. Likewise, comparable tectonostratigraphic evolutions suggests that these blocks are possibly of eastern Australian origin.

The East Chukotka block with the Novosibirsk and Wrangel Islands (Zonenshain et al.,1990: fig. 109, Fig.47), and the (North) Taimyr block with the Severnaya Zemlaya islands (Zonenshain et al.,1990: fig. 109, Fig.48) are related to the northern Alaskan terranes from which they became separated in the Late Cretaceous, with further separation of the (North) Taimyr block during the Tertiary evolution of the Gakkel Ridge in the Arctic region (Zonenshain and Natapov,1990; Zonenshain et al.,1990). Two interesting, but unresolved observations could possibly be interpreted in support of a former relationship with eastern Australia. Firstly, evidence for an Early Carboniferous deformation event in the Palaeozoic sedimentary cover of Severnaya Zemlaya has been related to the Ellesmerian Orogeny (Zonenshain et al.,1990), but could equally be related to the Kanimblan orogenic phase that has affected Australia so pervasively. Secondly, Late Permian assemblages from the nearby Nordvik Basin, parts of Novaya Zemlya and Spitsbergen, share at least 12 species of benthic foraminiferids with the Kazanian Ingelara Formation of the Bowen Basin (Palmieri et al.,1994). The occurrence of so many shared benthic foraminiferid species and also of an ancestral form of the key species P. borealis (Gerke) in areas that supposedly occupied antipodal positions during the Permian is hard to explain as the result of parallel evolution. Palmieri et al. suggested as possible solutions, either a reassessment of continental positions during the Permian, or the former operation of some unknown, but obviously potent, oceanic dispersal

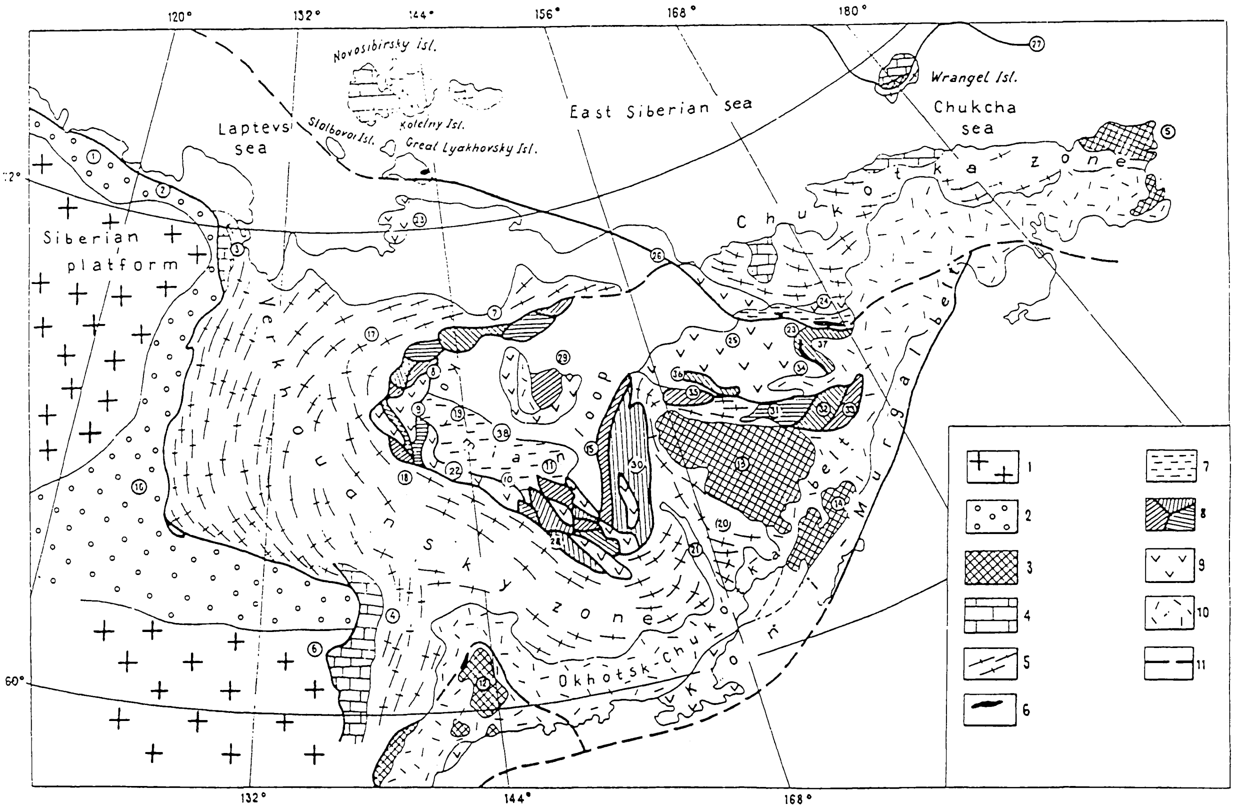


Figure 47 Tectonics of the Verkhoyansk-Kolymian belt, after Zonenshain et al. (1990, fig.109). Symbol legend: 1 = Siberian platform; 2 = Pre- Verkhoyansk foredeep; 3 = Precambrian massif; 4 = Lower Palaeozoic shelf carbonate complexes; 5 = Upper Palaeozoic and Mesozoic clastic series; 6 = ophiolite; 7 = South Anui suture zone (Late Jurassic-Early Cretaceous); 8 = various exotic terranes; 9 = Late Jurassic-Early Cretaceous subduction-related volcanics; 10 = Middle Cretaceous subduction-related volcanics (Okhotsk-Chukotka volcanic belt); 11 = main thrust and suture. Numbered units are: 1 = Pronchishchev zone; 2 = Chekanovsky zone; 3 = Kharaulakh zone; 4 = Sette-Daban zone; 5 = East Chukotka massif; 6 = Kyllakh uplift; 7 = Polousny zone; 8 = Selenyakh zone; 9 = Tas-Khayakhtakh zone; 10 = Chersky zone; 11 = Omulevka zone; 12 = Okhotsk massif; 13 = Omolon massif; 14 = Taiganos massif; 15 = West Kolymian block; 16 = Pre-Verkhoyansk foredeep; 17 = Oldzhoi trough; 18 = In'yaly-Debinsky synclinorium; 19 = Bastakh zone; 20 = Sugoi zone; 21 = Omsukchan graben; 22 = Uyandina-Yasachanaya arc; 23 = Anyui-Svyatoyannos arc; 24 = Nutesin arc; 25 = Alazei-Oloi arc; 26 = South Anyui suture; 27 = Herald-Brooks suture; 28 = Kolyma-Indigirka suture; 29 = Alazei terrane; 30 = Pri-Kolymian terrane; 31 = Ushurak-chan terrane; 32 = Levo-Oloi terrane; 33 = Eropol terrane; 34 = Aluchin terrane; 35 = Berezov terrane; 36 = Siver terrane; 37 = Yablonski massif; 38 = Zyryanka depression.

mechanism. On the basis of current knowledge of Australia's Permo-Triassic movement and the movement history of terranes that are now incorporated in the North American Cordillera, a highly speculative case could be made for an extraordinary northward movement of these terranes from a south polar to an Arctic location. Greater Australia as part of eastern Gondwana underwent a large-scale northward movement during the Triassic from a Permian south polar region to a low to moderate southern location by the Late Triassic. North American terranes of established eastern Tethyan, and presumably previously eastern Australian affinity, traversed the Palaeo-Pacific sometime before the Early

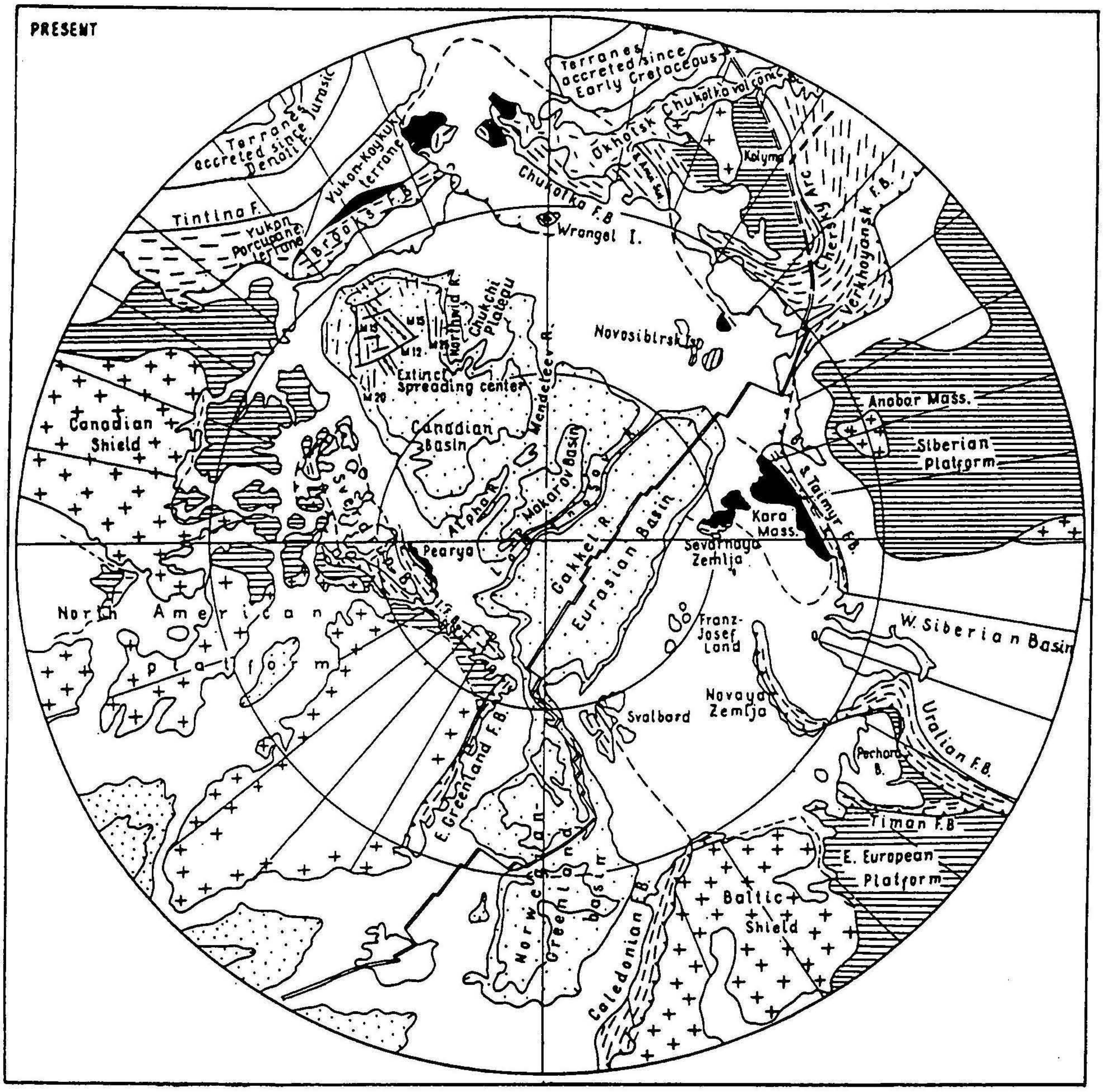


Figure 48 Main tectonic structures of the Arctic basin, after Zonenshain et al. (1990, fig.118) and Zonenshain and Natapov (1990, fig.1). Oceanic basins deeper than 2000m are dotted; contours are at 2000m and 3000m depths. Continental shields are shown by crosses, platforms by horizontal hatching and orogenic belts by dashed lines. Ancient massifs that are remnants of the Arctida continent are in black. Tooth lines correspond to thrust fronts. Thick lines mark main sutures.

Middle Jurassic. These terranes then became part of a large-scale northward moving conveyor belt that brought the terranes by the Late Cretaceous-Early Tertiary as far north as the northern Alaska-Chukotka region. Subsequent westward transport during Tertiary opening of the Arctic Basin may have moved the

Taimyr-Nordvik-Novaya Zemlya terrane much further westward to its current location at the northern rim of the Siberian craton. This is a highly speculative and extraordinary mobilistic hypothesis that can be tested by integrated biostratigraphic, palaeomagnetic and geochronologic studies. This is suggested as a possible subject for an Australian-Russian cooperative study, with secured success whatever the outcome. Rejection of the hypothesis will confirm the faunal observations as a classical example of parallel evolution. Support for the hypothesis will force fundamental rethinking of the magnitude of terrane motions and the extent to which original Greater Australian fragments have become spread across the globe.

STRATIGRAPHIC AND TECTONIC STUDIES OF MORE CONFINED SIGNIFICANCE

Young

Young (1981,1990,1993) analysed global patterns in the biogeography of mainly non-marine Devonian fish faunas using cladistic techniques (Young,1986). This showed a general picture of a high degree of endemism in the Early Devonian with a changeover to cosmopolitan faunas during the Middle to Late Devonian. More specifically for Greater Australia and the Cathaysian continents, this analysis implies that the Early Palaeozoic geographic proximity of the Cathaysian blocks and eastern Gondwana evolved during the Silurian-Early Devonian toward continental isolation, followed in turn by increasing continental affinity during the Middle to Late Devonian and establishment of significant faunal exchange between Australia and the South China block during the Late Devonian-Early Carboniferous (?latest Famennian-Tournaisian). There is little evidence for subsequent contact, but the Permo-Carboniferous vertebrate fossil record of Greater Australia and the Cathaysian continents is unfortunately too meagre to date the continental separation other than within this general interval.

The common occurrence of latest Devonian sinolepids in eastern Australia and South China has been stressed by Young (1990,1993), Rich and Young (1996) and Young and Janvier (in press).With further fish evidence for Middle Devonian amalgamation of an Asian "Superterrane" made up of the Tarim, North China, South China and Indochina blocks (Fig.49), Young (1990,1993) and Young and Janvier (in press) prefer a location of this superterrane off eastern Greater Australia, rather than the more conventional location off northwestern Greater Australia and northern Greater India (Fig.50). It should be noted that Shergold (1995) has described close biostratigraphic correlations for the Middle and Late Cambrian between northern and central Australia and the Cathaysian blocks including Sibumasu. Such an observation, however, may be non-discriminatory with regard to the two suggested Middle Palaeozoic locations of the "Superterrane".

Young and Janvier (in press) stress amalgamation of the Indochina, South China and Tarim blocks by the Late Silurian and clear separation of these Cathaysian continents from eastern Gondwana prior to the Middle Devonian (G. Young, pers. comm.,1997), reconnection to Asia and reassociation with Gondwana in the latest Devonian-Early Carboniferous (Young and Janvier, in press, fig.9), and followed finally by separation of the Cathaysian blocks from Gondwana sometime during the Permo-Carboniferous. The suggested separation prior to the Middle-Late Devonian, as based on vertebrate faunal evidence, is interesting if only for its follow-up story. This interpretation seems to have become embedded in several leading geodynamic evolution schemes (e.g. Nie Shangyou et al.,1990; Nie

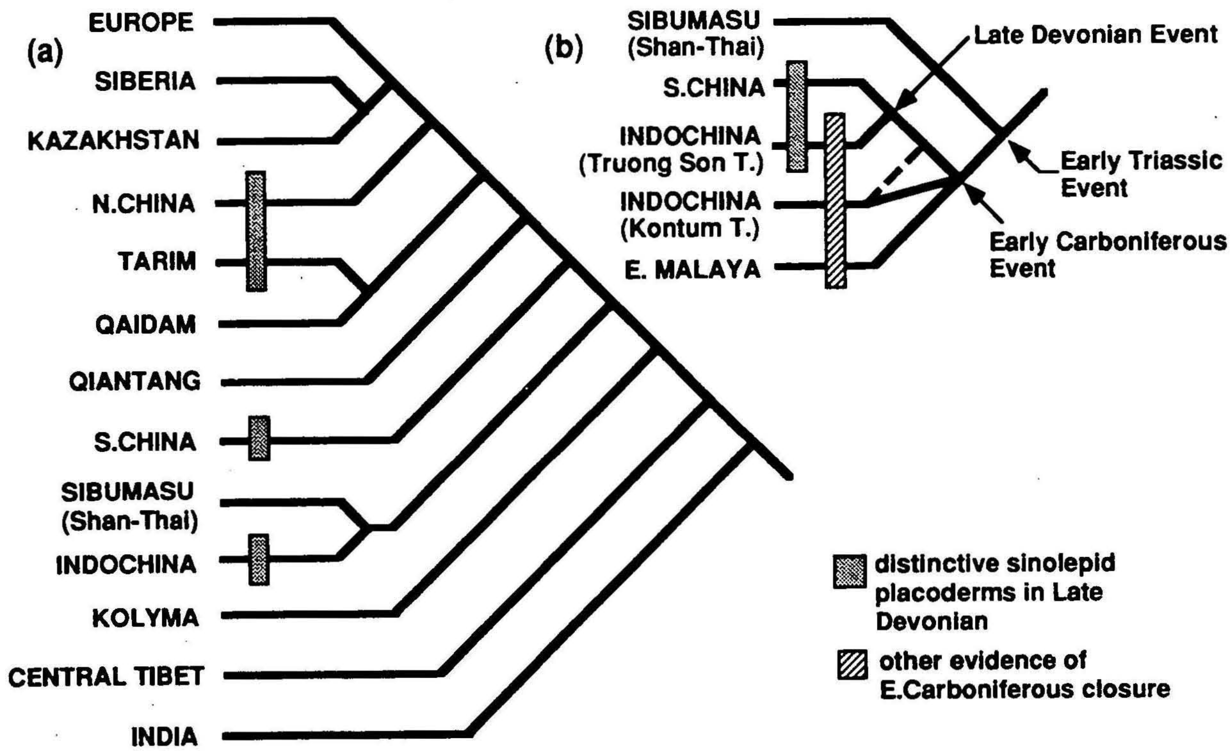


Figure 49 Cladistic representations of the accretionary sequence of Asian terranes (Young,1995, fig.10). A: Showing distribution of Devonian sinolepid placoderm fishes (Ritchie et al.,1992). B: Based on Metcalfe (1990). These sequences have been updated and extended by Young and Janvier (in press, fig.9).

Shangyou,1991) and may have been the springboard to interpret evidence for tectonic activity at that time, which does not seem highly discriminatory between a Gondwanan or Laurasian context of the Cathaysian continents, as further support for such a separation. Middle Palaeozoic palaeomagnetic data from the Cathaysian continents is sparse and in part of doubtful interpretation. It is unlikely that this hypothesis of separation by the Middle Devonian can be tested with available palaeomagnetic data.

Audley-Charles

In an early and daring reconstruction (Fig.51A) Audley-Charles (1983) proposed the former presence of a rim of continental blocks around the northeastern - Greater India - Greater Australia - margin of northeastern Gondwanaland. The reconstruction seems a combination of the early concepts of a Cimmerian Continent (e.g. Şengör,1979, though not acknowledged) and Pacifica (Nur and Ben-Avraham, 1978) rimming Greater Australia from the northwest to the east, combined with earlier suggestions (Ridd, 1971; Hamilton,1979; Mitchell,1981) that Indochina, the Malay Peninsula, Sumatra and Burma were part of Gondwana prior to the Permo-Triassic, and further based on Audley-Charles' substantial knowledge about Late Palaeozoic floral, faunal and lithostratigraphic evidence from Southeast Asia and Australia-

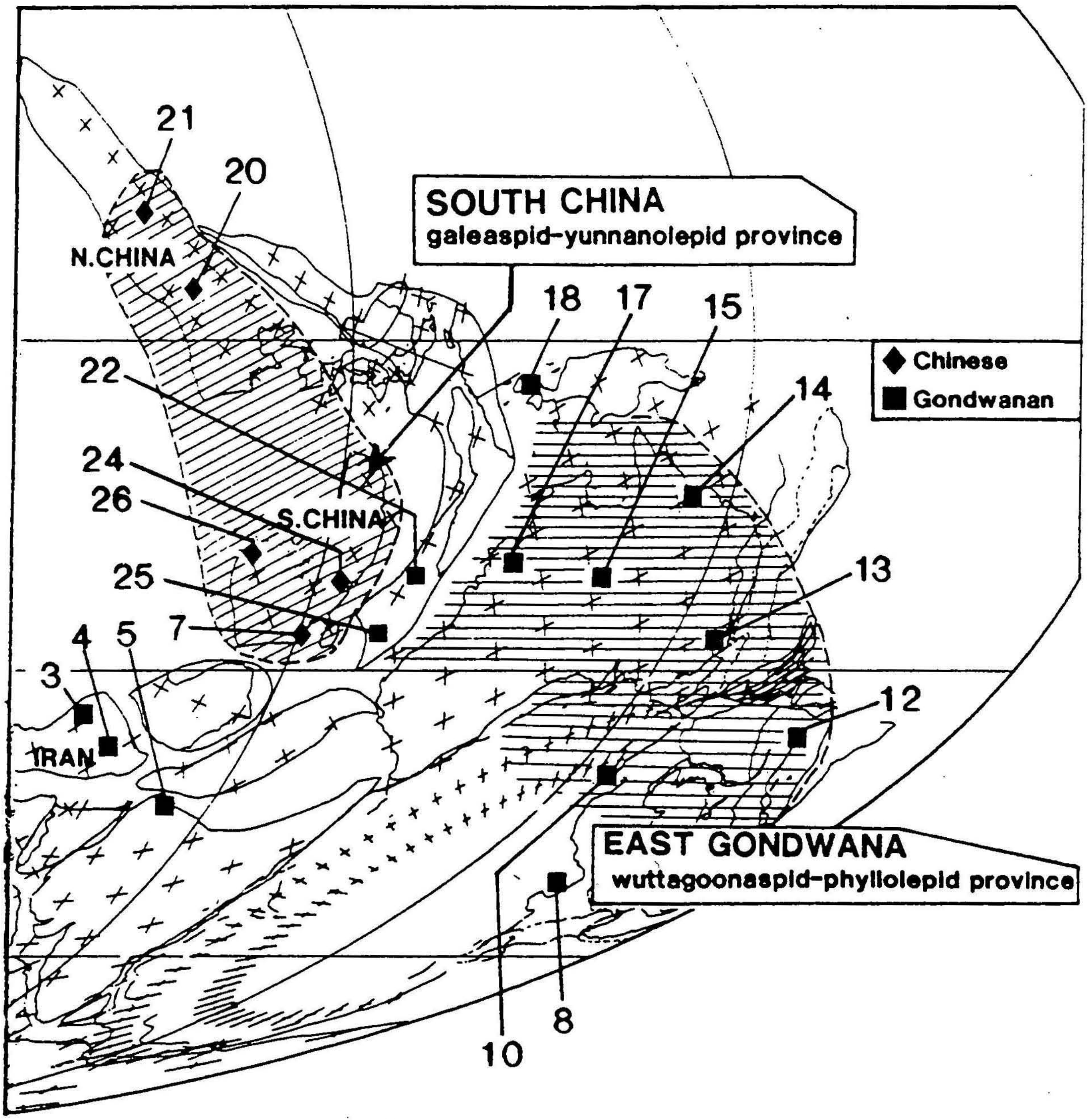


Figure 50 Reconstruction following Scotese and McKerrow (1990) showing the South and North China blocks relocated against northeastern Gondwana and thus bringing together completely different Early Devonian vertebrate faunal provinces, after Young (1993, fig.12.6). This reconstruction is considered most unlikely by Young (1990,1993) and Young and Janvier (in press), with an alternative reconstruction shown in Young and Janvier (in press, fig.1).

New Guinea. Audley-Charles suggests that separation of the Cimmerian Continent-Pacifica rim, in which he includes notably Indochina, occurred no earlier than Jurassic (Audley-Charles,1983; Audley-Charles et al.,1988). This is argued from his identification of a calc-alcaline arc of Middle to Late Triassic age throughout eastern Australia, central New Guinea, Sumatra, Borneo, Malaya, Thailand, Burma and South

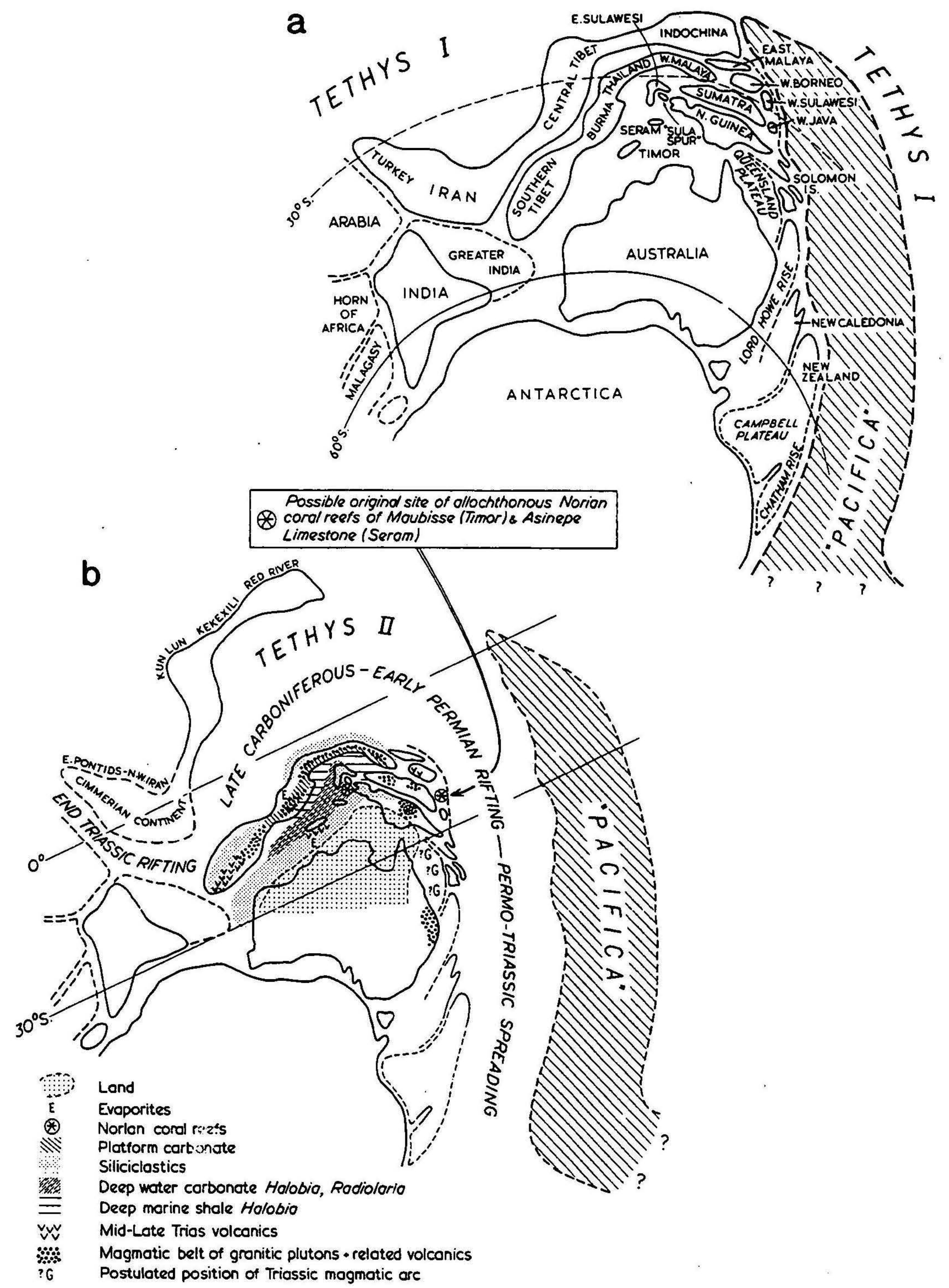


Figure 51 A: Reconstruction of eastern Gondwana during the mid-Carboniferous (320 Ma), after Audley-Charles (1983, fig.1). B: Reconstruction of eastern Gondwana during the Late Triassic (220 Ma), after Audley- Charles (1983, fig.2). Attention is drawn to the magmatic arc forming the continental margin of eastern Gondwana which appears related to spreading of the Tethys II Ocean.

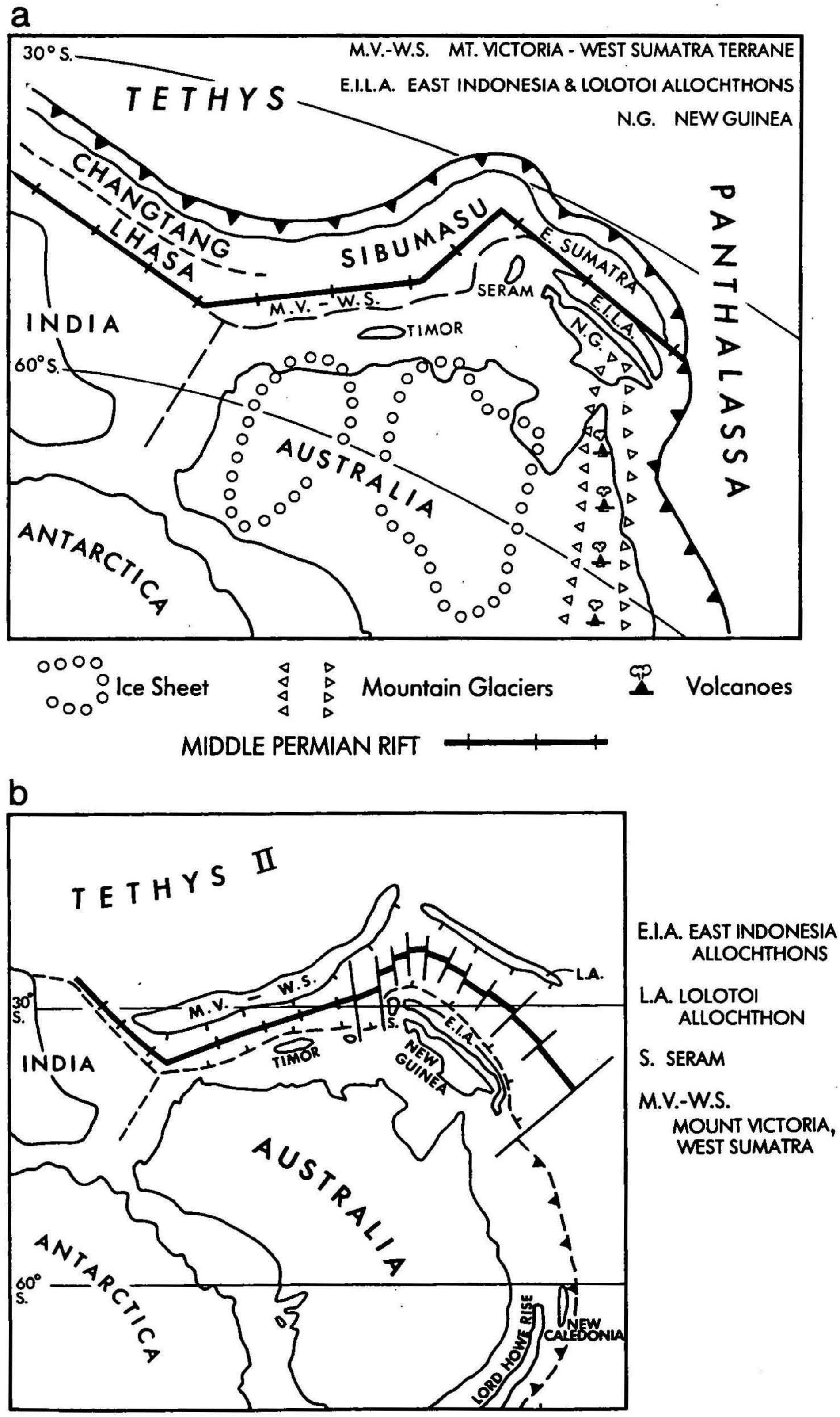


Figure 52 A: Early Permian palaeogeography of Greater Australia, after Audley-Charles (1991, fig.7).
B: Late Jurassic palaeogeography of Greater Australia, after Audley-Charles (1991, fig.8).

Tibet (Fig.51B). He accordingly argues (Audley-Charles et al.,1988) for Late Cretaceous, rather than Triassic-Jurassic, accretion of these fragments to Laurasia. His arc argument is rather unique and has not been followed by others. In a more recent paper Audley-Charles (1991) has adopted the more generally accepted Middle-Late Permian date of separation for the Qiangtang-Sibumasu-East Sumatra rim (e.g. Metcalfe,1990) in which he notably includes the Lhasa block (Fig.52A). A more internal rim of Mount Victoria Land, West Sumatra and the Lolotai allochthon of Timor (Audley-Charles and Harris,1990) is argued to separate during the Late Jurassic (Fig.52B), whereas fragments such as Timor, Seram and the East Indonesian allochthons (Pigram and Panggabean,1984; Burrett et al.,1991) separate during the Eocene.

Helmcke

Helmcke proposes from biostratigraphic and lithostratigraphic field evidence in southeastern Asia and analysis of the literature that the sutures of the Permo-Triassic Paleotethys should be searched for to the south and east of mainland China and Southeast Asia (Helmcke and Lindenberg,1983; Helmcke,1985). In his view the sutures are to be found to the south of the Lhasa block and to the west of the Shan-Thai block (Fig.53). This view is based on his interpretation that all identified sutures further to the north and to the east in mainland China and southeastern Asia were already closed by the Late Palaeozoic and thus cannot represent closure of the Permo-Triassic Paleotethys. The generally prevailing interpretation of current stratigraphic and tectonic evidence certainly is in disagreement with Hemcke's rather esoteric view.

Hutchinson

A well-documented factual overview of the origin of Southeast Asian terranes and their tectonic amalgamation is presented in Hutchinson (1989) and also in Gatinsky and Hutchinson (1986). Hutchinson argues that all terranes in Southeast Asia are of Gondwanan origin, but identifies two groups: a group with a Cathaysian floral affinity, and a "Gondwana" group characterised by the presence of both a Permian Glossopteris flora, Carboniferous-Permian diamictites of glacial origin, and cool-water Carboniferous-Permian faunas. His identifications are generally in agreement with the currently prevalent scheme of Ian Metcalfe. Hutchinson identifies Sumatra as an enigma, with a Cathaysian-type flora present in South Sumatra and Gondwanan affinities in North Sumatra. His suggestion, following Hamilton (1979), that the island is of composite nature, with continuation of the Bentong-Raub suture of Peninsular Malaysia separating the Shan-Thai and Indochina blocks through central Sumatra, has been accepted in Metcalfe's reconstruction schemes.

Hutchinson shows a set of palinspastic reconstructions which are heavily based on palaeomagnetic evidence which was produced prior to the recognition of widespread overprinting, and follows Burrett's arguments for an original position of "Gondwana" fragments against northern Australia, opposite the Georgina and Canning basins, with the Sinoburmalaya (Shan-Thai) block opposite northwest Australia. Hutchinson argues that blocks with Cathaysian floral affinities rifted away during the Ordovician and Silurian, and that blocks of Gondwanan affinity rifted from Australia during the Carboniferous, but remained in proximity till the Late Permian. Such views on the time of separation of the two groups of fragments do not follow mainstream ideas, but arguments in support of such a view are not clearly indicated.

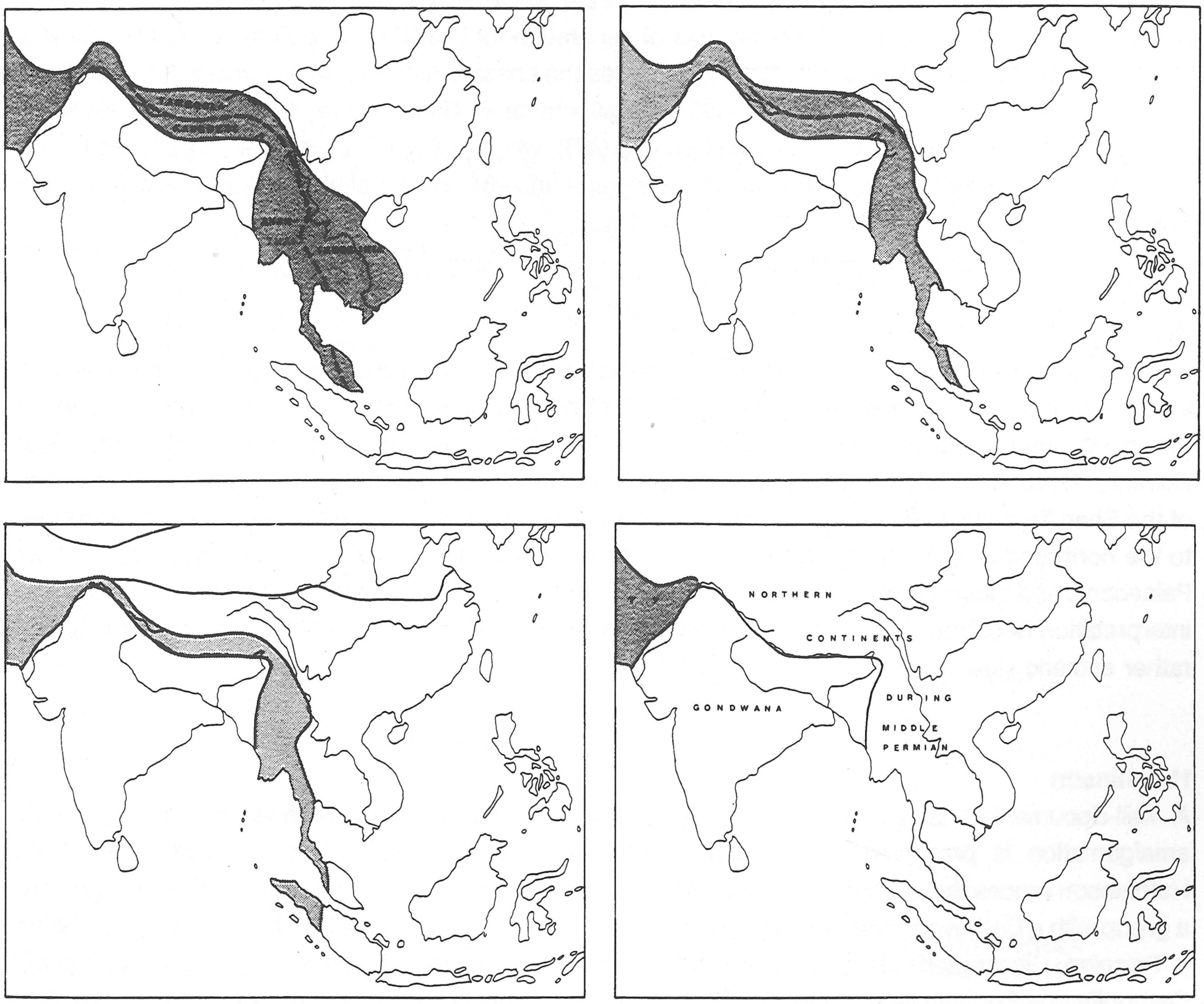


Figure 53 Various options for possible extension of suspect terranes of Gondwana origin in Southeast Asia and China, after Helmcke (1985, figs 1-4). A=mainly based on Šengör (1979); B=based on Stöcklin (1980); 3=based on Li Chunyu et al. (1980); 4=based on Helmcke (1985).

PALAEOMAGNETIC SYNTHESES

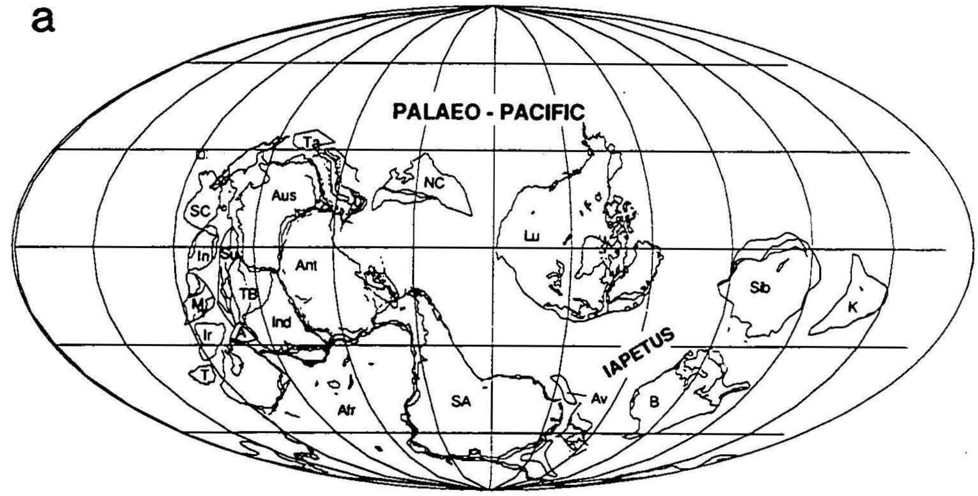
Palaeomagnetic activity in eastern and southeastern Asia has increased considerably with the opening of China to western workers in the late seventies. In addition there is a steady production of data by Chinese workers. Unfortunately activity by local workers in Thailand and Malaysia (e.g. Bunopas and Haile) has virtually stopped, but local activity in Vietnam is on the rise. Much of the earlier, and some of the more recent, palaeomagnetic activity did aim to reconstruct the original Gondwanan location of Asian blocks, but was hampered in this effort by widespread regional remagnetisation of Palaeozoic rocks in particular, whose pervasive effects have been recognised only lately. Thus of the many foreign groups working in Asia, only a few have to date made a considerable contribution to the Palaeozoic reconstruction of Greater Australia and Greater India. The attention of most groups has now turned to constraining the timing and evolution of Asia's deformation (e.g. the French group from IPGP, the German group from the Universities of Tübingen and München, the Royal Society consortium, the Swiss group from ETH, the Lamont Doherty Observatory, the University of Florida, the University of Michigan, and the University of California at Santa Barbara). Only a few groups have managed to acquire a coherent set of apparently reliable Palaeozoic data that are pertinent to the reconstruction problem addressed here. Such quality results have been obtained by the Stanford University group in the Tarim-Kunlun-Junggar region, the group from the University of California at Santa Cruz in the North and South China blocks, and the Santa Barbara group in Southeast Asia. Regional implications of new palaeomagnetic results have generally been explored on a seemingly ad-hoc basis in the many papers reporting the results. There are only few studies that tackle a regional synthesis of available data. One of the more outstanding of these is the recent synthesis by Zhao and coworkers (Santa Cruz) that is not only based on their own excellent work throughout North and South China, but also on the admirable work of the Stanford group in Western China and on an assortment of quality studies by workers from other groups. Zhao's synthesis will be reviewed here as a quality summary of current palaeomagnetic knowledge for China. In addition, a summary paper on Paleozoic global reconstructions by the University of Western Australia group, which is heavily based on palaeomagnetic control, will be reviewed. For a very readable and easily accessible regional overview of palaeomagnetic control on the accretionary evolution and deformation of southern and eastern Asia, I refer any interested reader to Van der Voo's (1993) book, but will not address this impressive synthesis here as it falls outside the scope of this review.

Li Zheng Xiang and coworkers (University of Western Australia)

Li and his coworkers have produced a set of six global reconstructions covering the Palaeozoic which are primarily based on palaeomagnetic data, with additional recourse to palaeoclimatic and biogeographic data. The palaeomagnetic database for the Gondwana continents is heavily based on Australian data whose interpretation may be generally accepted as far as the Early Palaeozoic is concerned, but is of uncertain definition for the Middle Palaeozoic, and is disputed for the Late Palaeozoic. This dispute is touched upon, but not addressed in any great detail, in Li et al's description of the Palaeozoic APWP (Li et al.,1993b,1994a). An overview and comparison of the two alternative interpretations of the Late Palaeozoic APWP for Australia and Gondwana is provided in the palaeomagnetic analysis section in part two of this review (Record 1995/52).

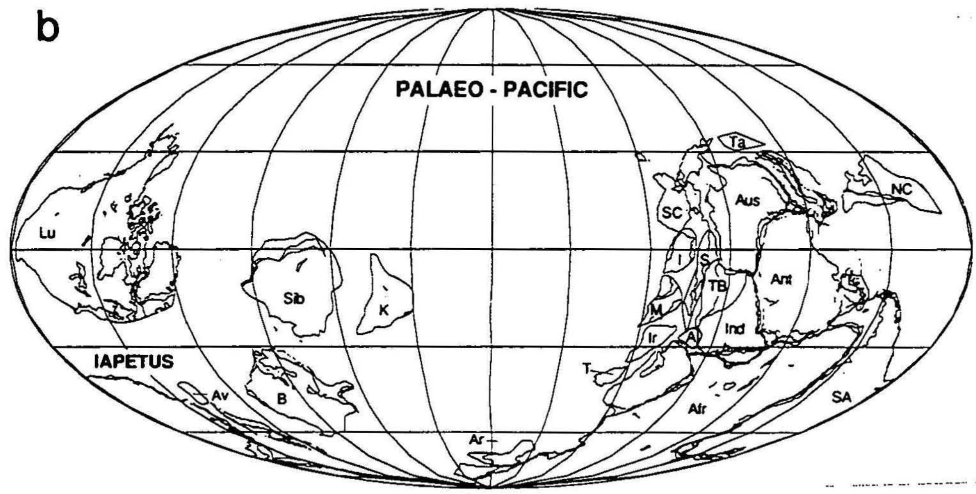
Li's reconstructions (Figs 54A-G) are presented as full global views, so they can be easily compared with Scotese's global reconstructions. The Cambro-Ordovician reconstructions (Fig.54A,B) show positions of the Chinese and Southeast Asian fragments which are clearly defined with respect to Greater Australia and Greater India. Thus South China is reconstructed opposite Irian Jaya, Sibumasu against northwestern Australia, the Tibetan blocks adjacent to or as part of Greater India, and Afghanistan between Arabia and northwestern India. Indochina, Malaya, Iran and Turkey are positioned further outboard. The Tarim block is positioned opposite northeastern Queensland and the North China block is located somewhat oddly off Tasmania as a reminder of its location within Rodinia. Kazakhstan is regarded as already in close proximity to Siberia. This Early Palaeozoic reconstruction notably differs from Neoproterozoic reconstructions that have been proposed more recently by Li and coworkers. For

a



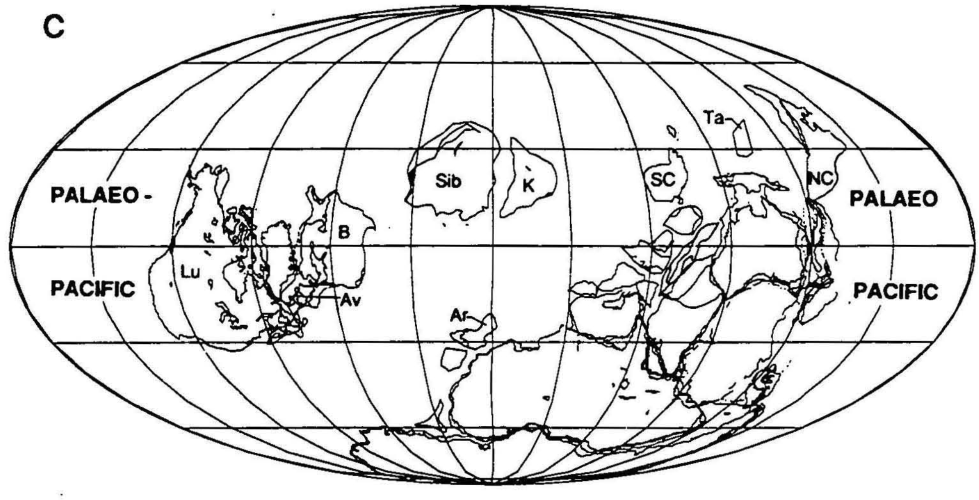
Cambro-Ordovician

b



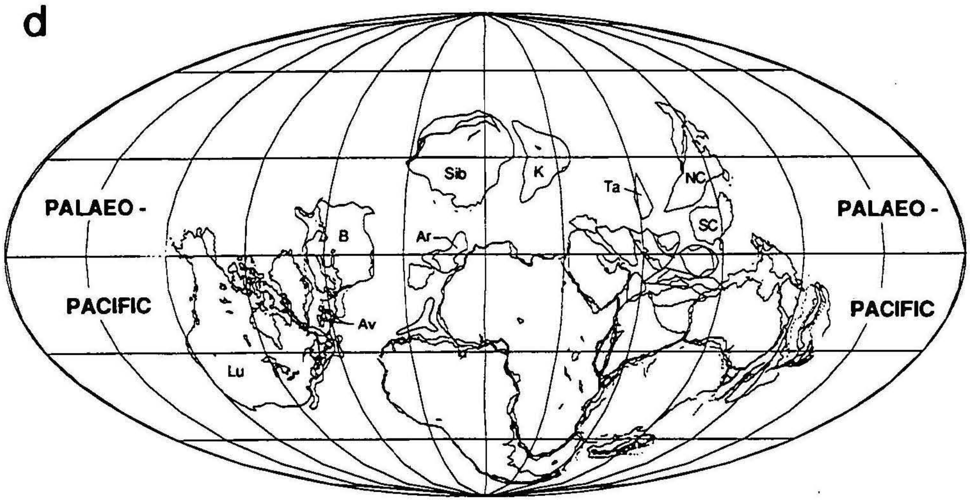
Cambro-Ordovician

c



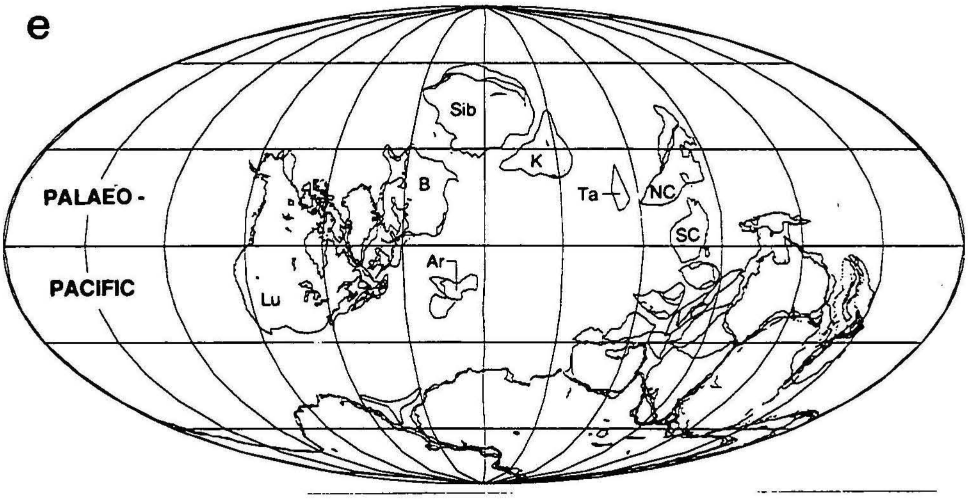
Mid-Silurian

d



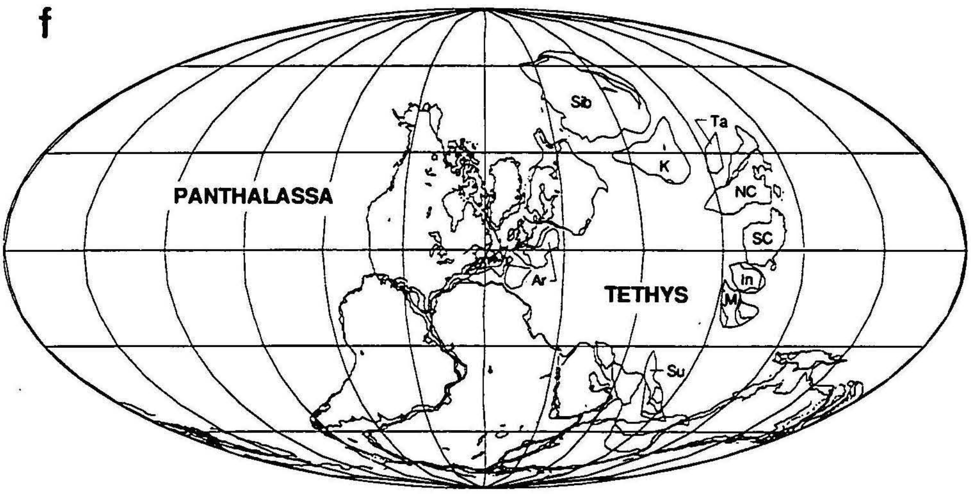
Early Devonian reconstruction.

e



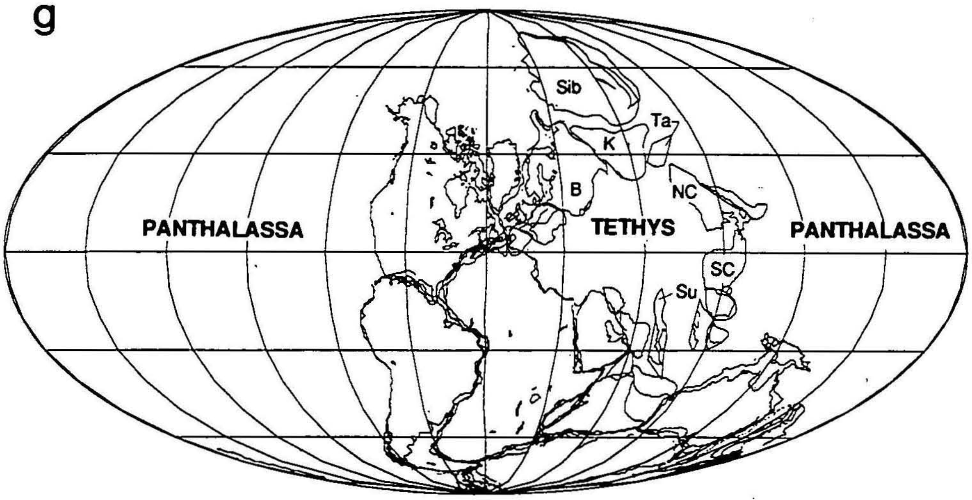
Late Devonian reconstruction.

f



Late Carboniferous reconstruction.

g



Early to mid-Permian

Figure 54 [previous pages and above] Palaeozoic global reconstructions after Li et al. (1993b). Legend: SA=South America, Lu=Laurentia, Av=Avalonia, B=Baltica, K=Kazakhstan, Sib=Siberia, Afr=Africa, Ar=Arabia, T=Turkey, Ir=Iran, Af=Afghanistan, Ind=India, TB=Tibet, Ta=Tarim, NC=North China, SC=South China, In=Indochina, Su=Sibumasu, M=East Malaya, Bo=SW Borneo, Aus=Australia, Mad=Madagascar, Ant=East Antarctica.
A,B: Cambro-Ordovician reconstruction (ibid., figs.2.3, 2.4).
C: Mid-Silurian reconstruction (ibid., fig.2.5).
D: Early Devonian reconstruction (ibid., fig.2.6).
E: Late Devonian reconstruction (ibid., fig.2.7).
F: Late Carboniferous reconstruction (ibid., fig.2.8).
G: Early to middle Permian reconstruction (ibid., fig.2.9).

instance Li et al. (1995,1996) argue for a Rodinia configuration with the South China block, not North China and Tarim, positioned between eastern Australia and northwestern America. Li et al. (1994b,1996) and Zhang et al. (1994) argue on mainly lithostratigraphic grounds for a position of the Tarim block opposite the Kimberley block, not opposite northeastern Queensland, and also argue that the Neoproterozoic stratigraphy of the North China block is comparable to northwestern Laurentia and Siberia but shares little similarity with Australia. A hypothetical rearrangement of the North and South China blocks versus eastern Gondwana from the Late Neoproterozoic to the Early Palaeozoic configuration is proposed in the context of the Late Neoproterozoic-earliest Palaeozoic Rodinia to Gondwana transformation (e.g. Li et al.,1996, figs 4,8-11).

The middle Silurian reconstruction (Fig.54C) shows the majority of the Cathaysian fragments, North China, South China and Tarim, already separated from Greater Australia. Their northward movement continues during the Devonian (Figs 54D,E). The Late Carboniferous reconstruction (Fig.54F) shows separation of Indochina and Malaya, whilst Sibumasu has edged toward Iran, where it still resides in the Early to middle Permian (Fig.54G).

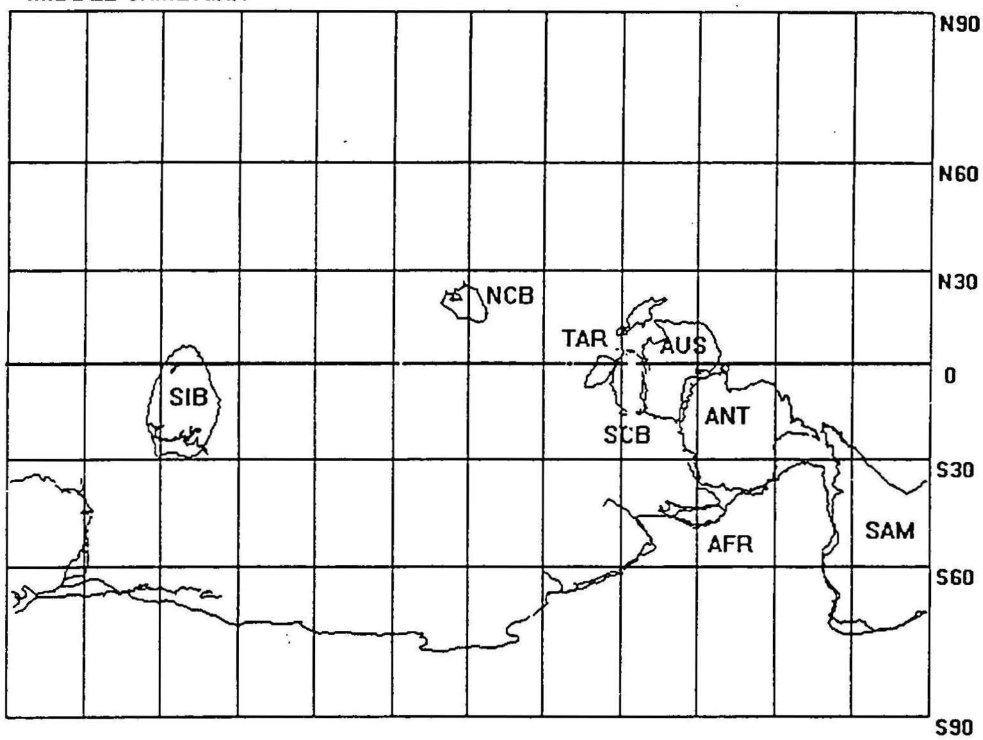
Zhao and coworkers (University of Santa Cruz)
Zhao et al. (1996) have compiled a critical selection of Phanerozoic palaeomagnetic data for the major Chinese blocks, i.e. North China, South China, Tarim and the Alashan/Hexi corridor. The compilation is to some extent additional to Enkin et al.'s (1992) extensive compilation of Permian and younger results for China. The emphasis is thus on Early and Middle Palaeozoic results. The compilation carries considerable authority because Zhao has been one of the main suppliers of high quality Chinese palaeomagnetic results.

Zhao et al. present a series of reconstructions covering the Middle Cambrian to Early Permian (Figs 55A-E) that show original positions and subsequent drift of the various Chinese blocks versus the Greater Australian part of Gondwana. The reconstructions are palaeomagnetically derived, but their discussion touches upon considerable stratigraphic and tectonic detail, from China and Australia in particular. For all their authority, the reconstructions suffer from some fundamental shortcomings in the approach that has been followed. Thus they are based on matching of single pole positions for the three Chinese blocks with selected single pole positions for one of the Gondwanan continents. This procedure does nothing to overcome problems related to mismatch in age of individual results or related to precision errors of individual results. Clearly, matching of the Early to Middle Palaeozoic polepath trajectories for the Chinese blocks with the Australian polepath could have alleviated this shortcoming. Another shortcoming is the neglect in these reconstructions of the former positions of the Sibumasu and Indochina blocks that are clearly of Gondwanan origin. For instance the various reconstructions show palaeomagnetically derived positions of the North China and South China block against northwestern Australia, whereas Early Palaeozoic biostratigraphic evidence suggests that Sibumasu occupied such a position. Another well-known palaeomagnetic problem is the polarity uncertainty of Chinese Palaeozoic results. This can be attributed to a widespread Middle Palaeozoic gap in the stratigraphy and the absence therefore of an evolutionary record of continental movements that may have occurred during that time.

The Middle Cambrian reconstruction (Fig.55A) shows South China positioned against northwestern Australia with Tarim further outboard. An inverted North China is placed at some distance to the northwest. Gondwana is positioned according to a single result from Antarctica. The Early Ordovician reconstruction (Fig.55B) shows a quite similar configuration, with South China still close to northwestern Australia, North China considerably closer, and the Tarim drifting slightly toward Greater India's northern margin. Again Gondwana is positioned according to a single result from Antarctica. The Early Silurian configuration (Fig.55C) surprisingly shows a musical chairs exercise of the North and South China blocks. North China is now located opposite to Australia's northwestern margin, South China opposite to the Exmouth Plateau, and Tarim opposite eastern Arabia. Gondwana is positioned according to a mean palaeopole derived by Van der Voo (1993). The Middle Devonian reconstruction (Fig.55D) implies considerable drifting. The Tarim block is located north of Arabia and the North and South China blocks are at some distance from northwestern Australia. These Chinese blocks have moved only slightly northward with respect to their Early Silurian positions. Most of the separation seems based on movement attributed to Gondwana according to the selected mean pole. Zhao et al. cite the development of highly endemic Early-Middle Devonian vertebrate faunas in both the North and South China blocks (Burrett et al.,1990; Young,1990) in support of the separation, but do not mention Young's evidence (e.g. Rich and Young,1996; Young and Janvier, in press) for a Late Devonian biostratigraphic link between the South China block and the Lachlan region of eastern Australia. The Early Permian

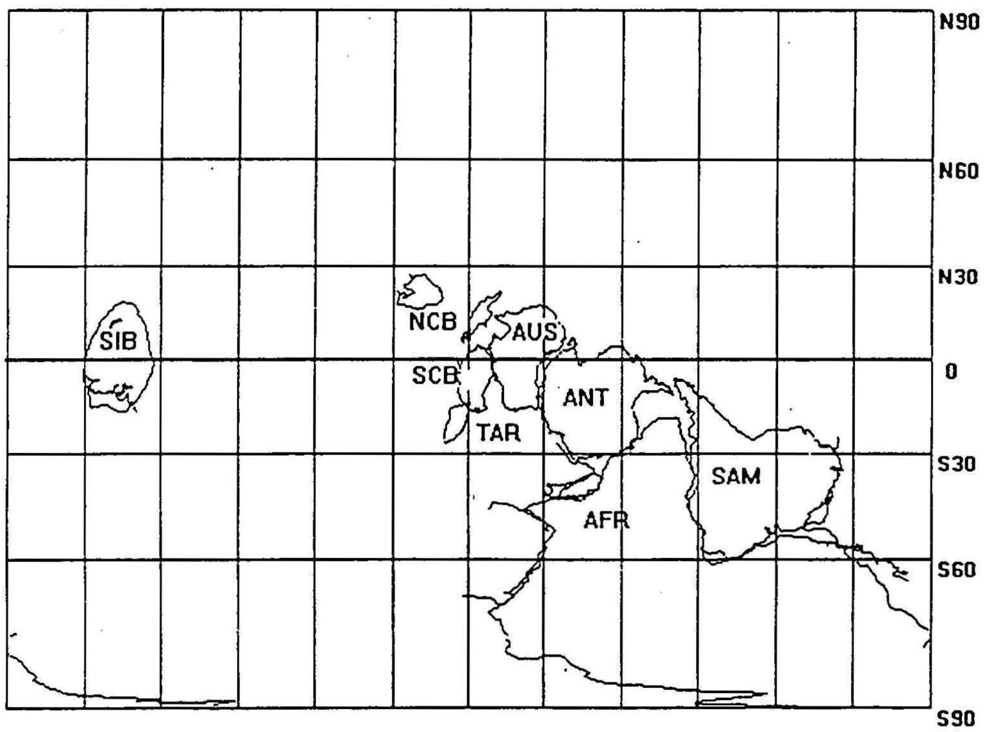
a

MIDDLE CAMBRIAN



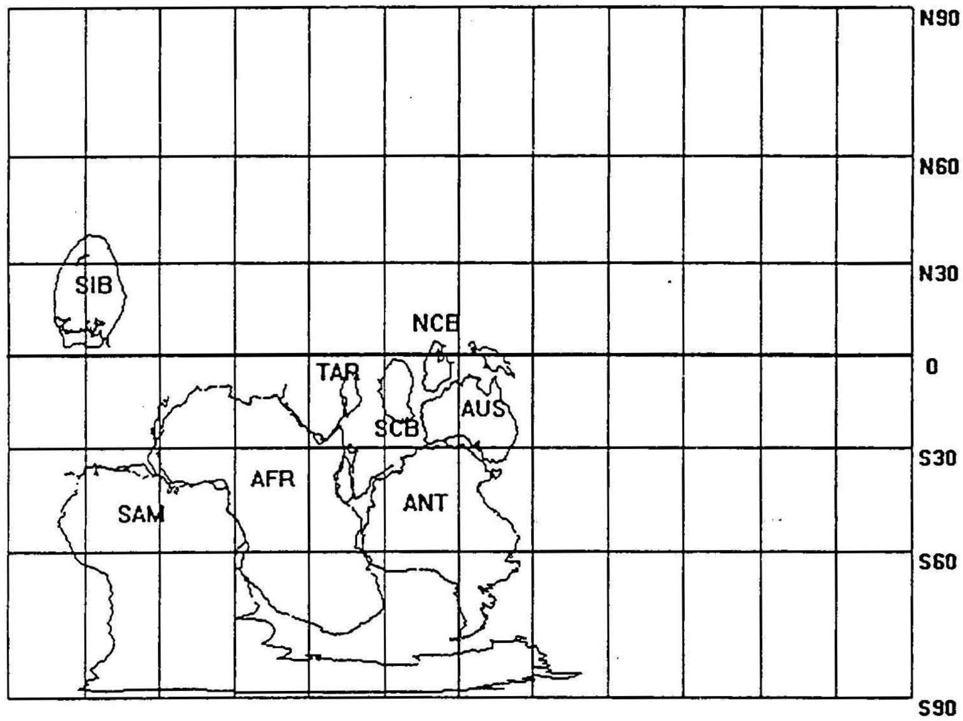
b

EARLY ORDOVICIAN



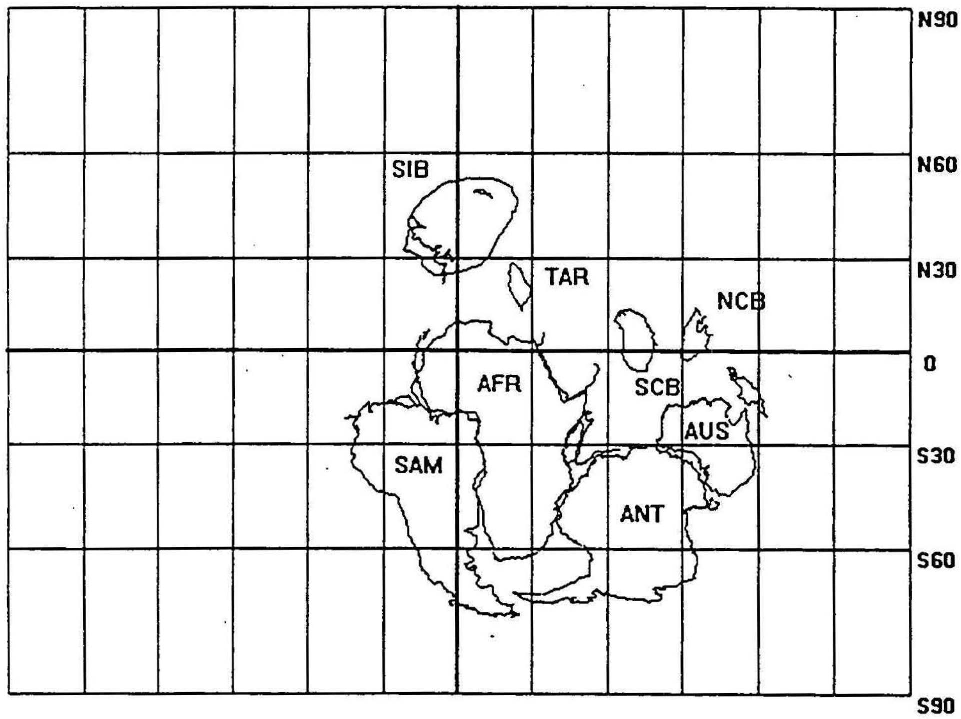
c

EARLY SILURIAN



d

MIDDLE DEVONIAN



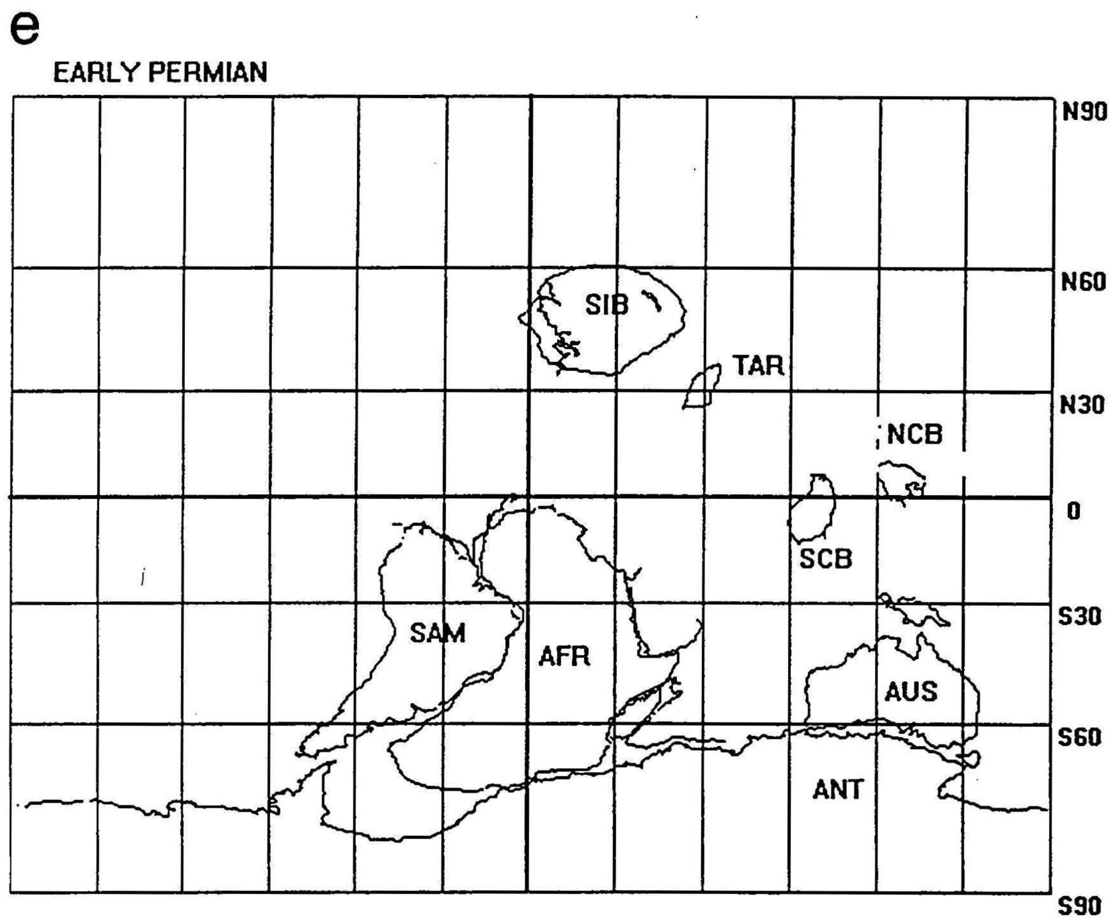


Figure 55 [previous pages and above] Palaeozoic reconstructions of Cathaysian fragments versus Gondwana, after Zhao et al. (1996).
A: Middle Cambrian reconstruction (ibid., fig.4)
B: Early Ordovician reconstruction (ibid., fig.5).
C: Early Silurian reconstruction (ibid., fig.6)
D: Middle Devonian reconstruction (ibid., fig.7).
E: Early Permian reconstruction (ibid., fig.10).

reconstruction (Fig.55E) shows much greater separation. Again this is due to the palaeomagnetically derived southward movement of eastern Gondwana. The three Chinese block have more or less maintained their Middle Devonian latitudinal positions.

Zhao et al. stress the consistent observations of low latitudinal positions for the Chinese blocks. They regard this as a reality and not as a possible artefact due to widespread Late Palaeozoic remagnetisation or inclination errors. Zhao et al. interpret latest Palaeozoic and Mesozoic palaeomagnetic results in terms of major diachronous closure amongst the Chinese blocks and closure of those blocks with respect to Eurasia. Thus, North China and Mongolia underwent a prolonged westward-progressing closure from

Late Permian to the Late Jurassic, whereas North and South China underwent an eastward progressing closure during the same period.

SOME CONCLUDING OBSERVATIONS

Northwestern Greater Australia - Northern Greater India

The various reconstruction models show general agreement for an original position of the Sibumasu block opposite northwestern Australia, with the North China block in near proximity. An uncontested addition to this configuration is a western extension of the Sibumasu block with the Qiangtang block off northern Greater India, and parallel and more inboard positions for the West Victoria Land (West Burma/Woyla) and Lhasa blocks. The positions of the South China and Indochina blocks are less clear, although there seems some consensus for locations off northern Greater India, perhaps near western Greater Australia. The positions of the Kazakhstan and Tarim blocks are not well-defined, other than that (southern) Kazakhstan was in an outboard position, being the first recognised Gondwana fragment to have dispersed. Tarim must have been in a nearby outboard position, although opinions vary as to whether it drifted in some association with Kazakhstan during its Middle(?) Palaeozoic separation, or dispersed later.

Northeastern and Eastern Greater Australia

There are strengthening geological and palaeomagnetic arguments for an Early to Middle Palaeozoic position of the Alexander terrane opposite the Lachlan Fold Belt, and perhaps also for the Omolon terrane opposite Queensland. There is strong biogeographic evidence that at least some of the terranes in the North American Cordillera e.g. Cache Creek and Eastern Klamath, occupied an eastern Tethyan/western Pacific position prior to their Triassic crossing of the Panthalassic Ocean. If the terranes in the North American Cordillera and in northeastern and northern Russia ever did occupy positions off eastern Australia, they most probably separated sometime before the Late Carboniferous (late Visean-Namurian) high-speed southward drift of Greater Australia as suggested by their low latitude Permian fauna. It seems most likely that these "Pacifica" terranes remained behind with the Cathaysian continents in low latitude positions when Greater Australia started its fast southward movement. A possible mechanism for such a movement pattern will be discussed in the section on palaeomagnetic data from suspect Gondwanan terranes in part two of this contribution to the North West Shelf project (Record 1996/52).

Taimyr block and Nordvik Basin

The dilemma of the original Late Permian polar position of the Nordvik Basin, Arctic or Antarctic, remains fascinating. Does the extraordinary similarity between Late Permian foraminiferae from the Nordvik Basin and the Ingelara Formation of Queensland indicate original proximity or, perhaps, an unbelievable case of homologous evolution? A case can be made for original proximity, provided that northward drift of the Nordvik Basin with Greater Australia during the Triassic and a further Triassic crossing of the Panthalassic Ocean together with the North American terranes can be established. Subsequent further northward movement along the North American Cordillera and beyond, along Russia's northern margin, can be argued for on the basis of established Late Mesozoic and Cenozoic movement patterns of the

Pacific and Arctic plates. This dilemma represents a prime case to test the unimaginable magnitude of terrane movements along the (Palaeo-) Pacific and Arctic Ocean.

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