PALAEOGEOGRAPHY 39

PERMIAN COAL AND PALAEOGEOGRAPHY OF GONDWANA

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by

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SUMMARY

Five palaeogeographic maps depict the possible age, distribution and palaeoenvironments of Permian rocks throughout Gondwana. The maps are based on published information and were compiled using the 1:10 million scale Gondwana reconstruction of de Wit and others (1988). The five time slice intervals selected - Asselian, Sakmarian, Artinskian-Kungurian, Ufimian-Kazanian and Tatarian-Dorashamian - represent major events or changes in palaeogeography that have influenced the accumulation of peat deposits during the Permian. A structure map shows features that were probably active during the Permian, and the distribution of preserved sediments and volcanics. A series of lithostratigraphic summary columns show the present state of knowledge of Permian stratigraphy throughout Gondwana. The age control of Permian sequences in Gondwana is becoming increasingly more accurate, however numerous problems still exist, especially with respect to inter-continental correlations.

During the Permian, the Gondwanan supercontinent extended from the equator to the polar region. Tectonic regimes on the margin of Gondwana range from a convergent (continent-continent) plate margin in the northwest, to a complex, ?transpressive convergent (continent-oceanic/terrane) margin in the southern Samfrau orogen. In contrast, the northeastern Tethyan margin of Gondwana shows evidence of active rifting during the Permian associated with the formation of the Neo-Tethys. A variety of sag and intracratonic rift basins developed in the interior of the supercontinent especially in regions of pre-existing basins and structures, possibly due in part to changes in stresses generated at the Gondwanan margin.

The main controls on Permian peat accumulation, distribution and preservation in Gondwana were palaeoclimate and tectonics. Following the widespread glaciation that dominated earliest Permian depositional environments thoughout the supercontinent, peat began to accumulate in cold, humid climatic conditions in post-glacial fluvial, lacustrine and paralic depositional systems. The main coal forming period during the Permian occurred in the Artinskian-Kungurian (late Early Permian), when thick peat swamps were present throughout the high-latitude Gondwann supercontinent; these deposits are preserved in a wide range of tectonic and depositional environments. By the Late Permian, coal deposition was generally restricted to eastern Gondwana (Australian, Antarctic and Indian regions) as Gondwana rotated northwards and aridity increased in the western and central regions of Gondwana. Tectonic subsidence and sedimentation rates, palaeotopography, floral changes, depositional environments, eustatically controlled changes in base level and marine transgressions were the dominant factors controlling the thickness, geometry, composition and dimensions of the coal seams.

INTRODUCTION

Objectives

The objective of this report is to summarise and discuss a series of palaeogeographic maps that were produced in an attempt to synthesise the distribution of Permian Gondwanan coal occurences and their relationship to sedimentary, tectonic and climatic palaeoenvironments. This report is part of a research program on Permian coal deposits conducted by BHP-Utah Minerals Coal Group and is an extension of previous studies on India, Southern Africa, Australia and South America coal deposits.

Method

To undertake such a project an extensive series of 135 summary stratigraphic columns (see Figure 3 for location) summarising the stratigraphy and depositional environments of Permian sequences of Gondwana have been compiled in Figure 4 (1-9). Where possible, the Permian sequences have been biostratigraphically correlated with the recently produced Permian chronostratigraphic scheme of Archbold & Dickens (1991) (Figure 1).

Time slice intervals throughout the Permian were selected using this correlation chart; they represent major geological features or events that influenced the deposition of peat, and the formation of Permian basins in Gondwana. Five time slices were chosen: 1. Latest Carboniferous - Asselian; 2. Sakmarian; 3. Artinskian - Kungurian; 4. Ufiman - Kazanian; 5. Tatarian - Dorashamian.

Lithological data for each of the time intervals were plotted on a pre-continental drift reconstruction of Gondwana (de Wit and others, 1988). The data maps have not been included in this report. Corresponding interpreted palaeogeographic maps were produced for each of the five time intervals (Plates 2-6). A structural features map (Plate 1) depicting Permian basin boundaries, igneous activity and fault movements was also compiled to indicate structural features that influenced deposition and palaeogeography.

Many of the Permian basins throughout Gondwana have been mapped and geological data collected and documented by Geological Surveys, exploration companies and academic institutions since the late nineteenth century; the economic coal basins in particular have been intensively studied. The quality of modern geological information varies throughout each continent; data available for most of the coal basins is of high quality and quantity, whereas information is poor or non-existent for subsurface, poorly preserved or geographical remote sequences, in for example central and north Africa, central South America and Antarctica. Nevertheless, there is sufficent data available to produce comprehensive summary stratigraphic columns throughout Gondwana. The palaeogeographic maps

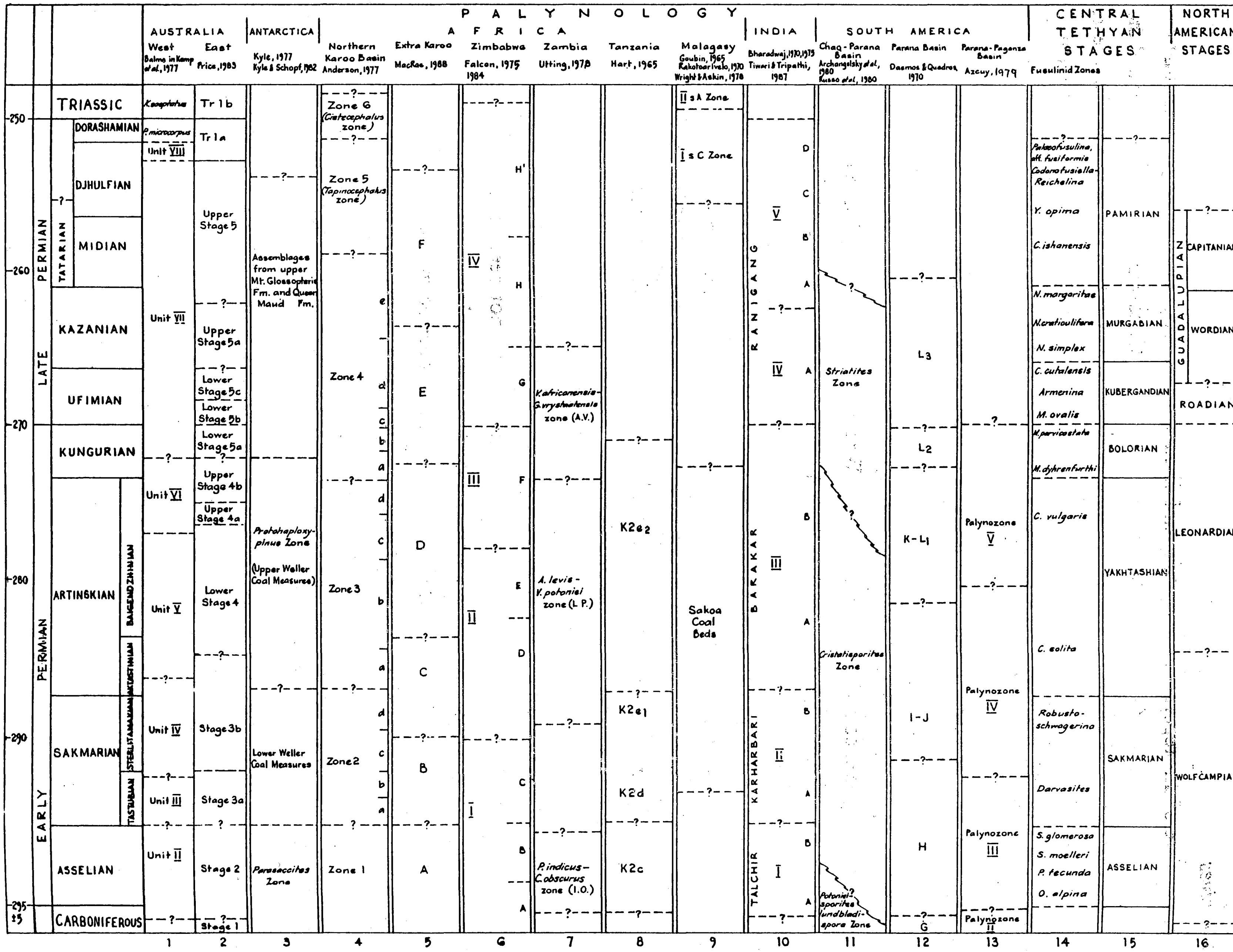

Figure 1. Biostratigraphic Correlation Chart

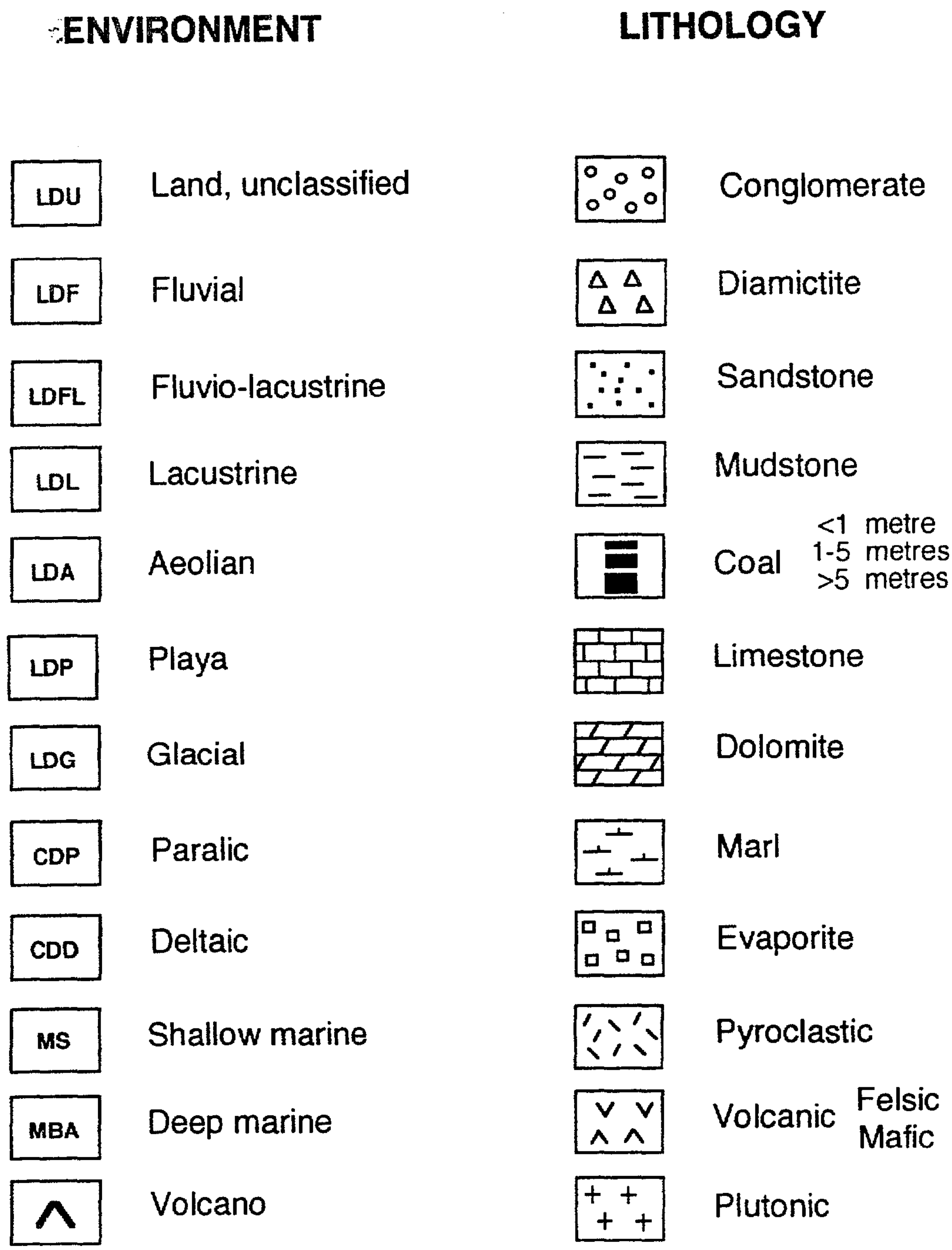

Figure 2. Environment and Lithology Legend

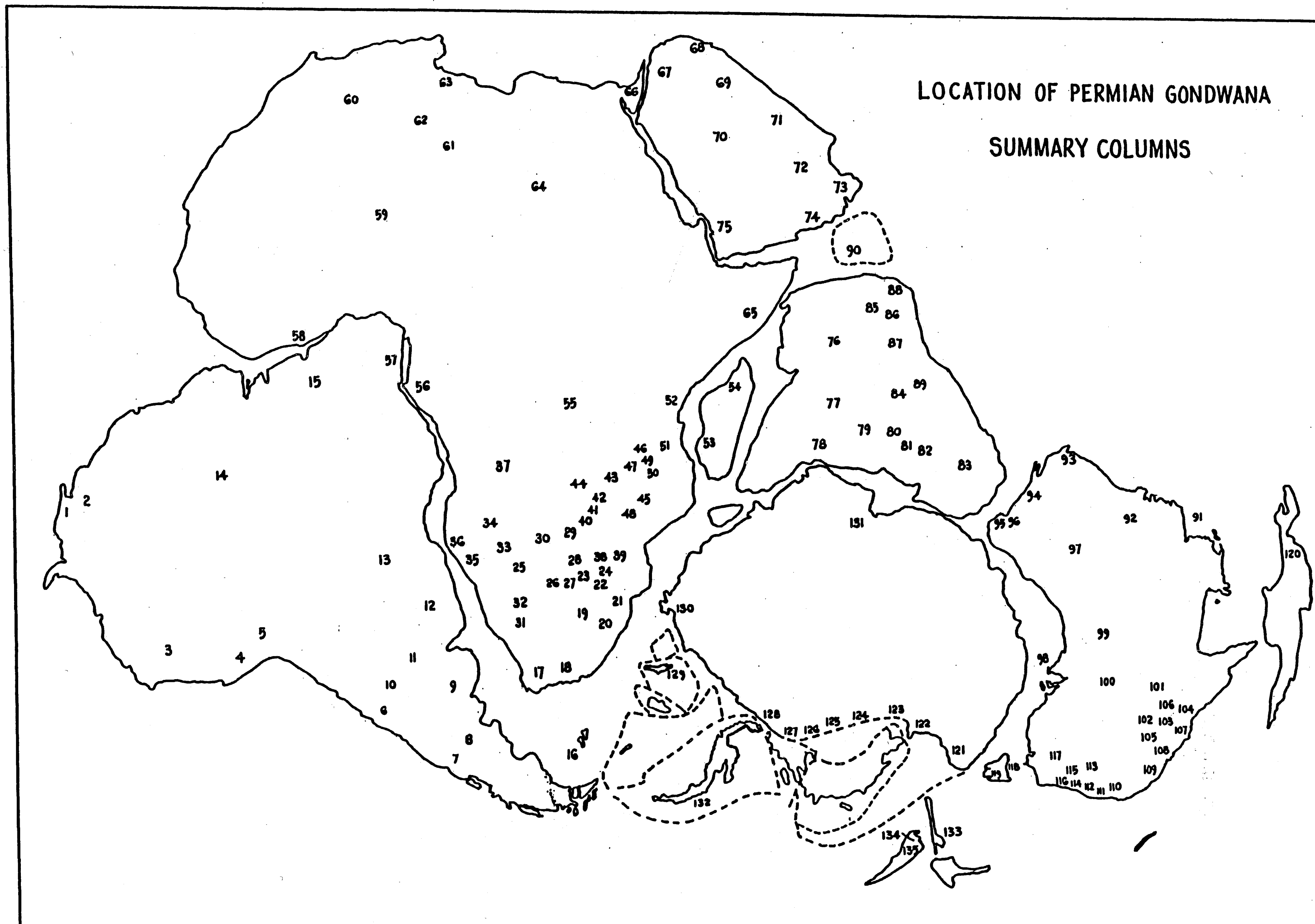

Figure 3. Location of Summary Stratigraphic Columns

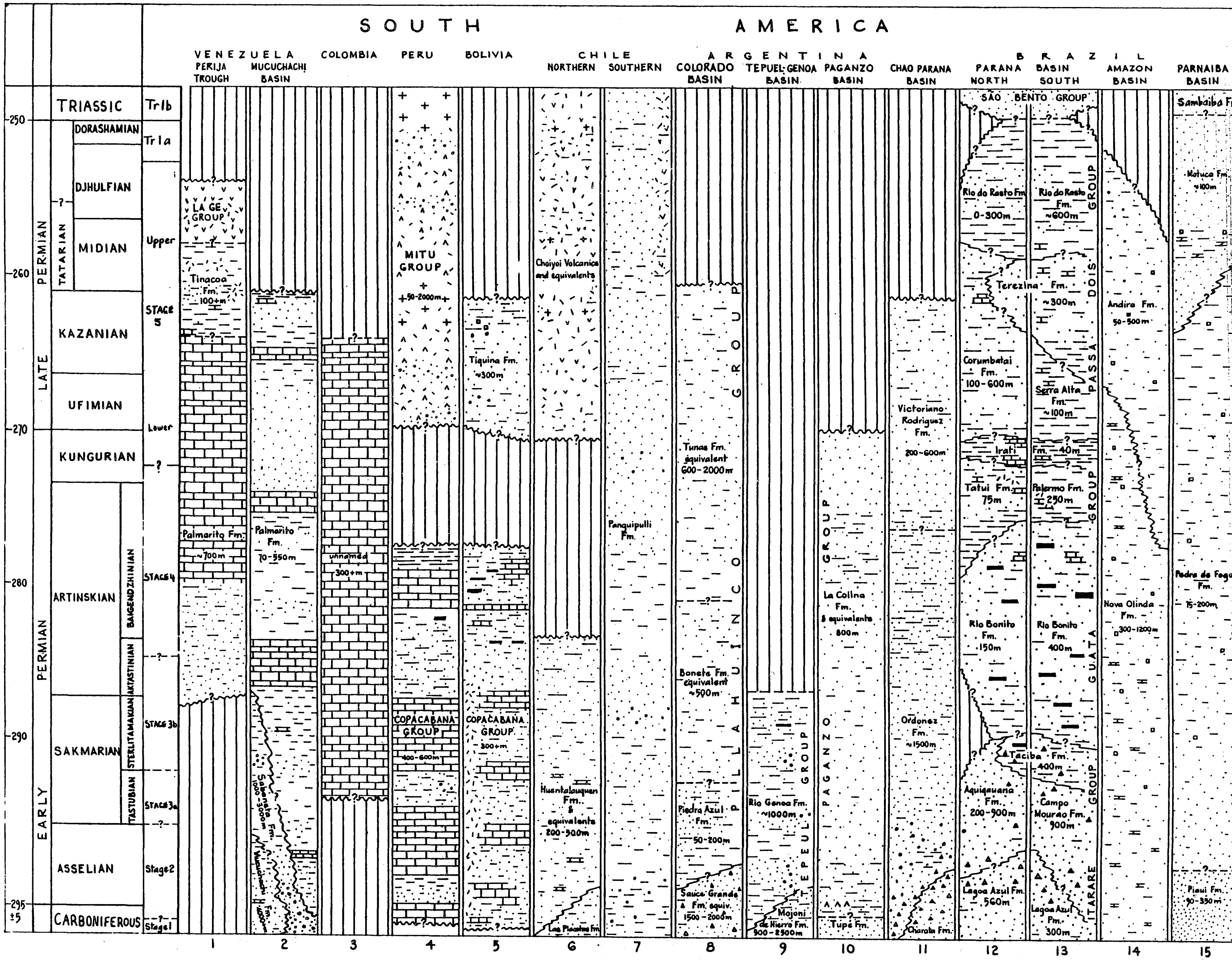

Figure 4. Stratigraphic Summary Columns (1)

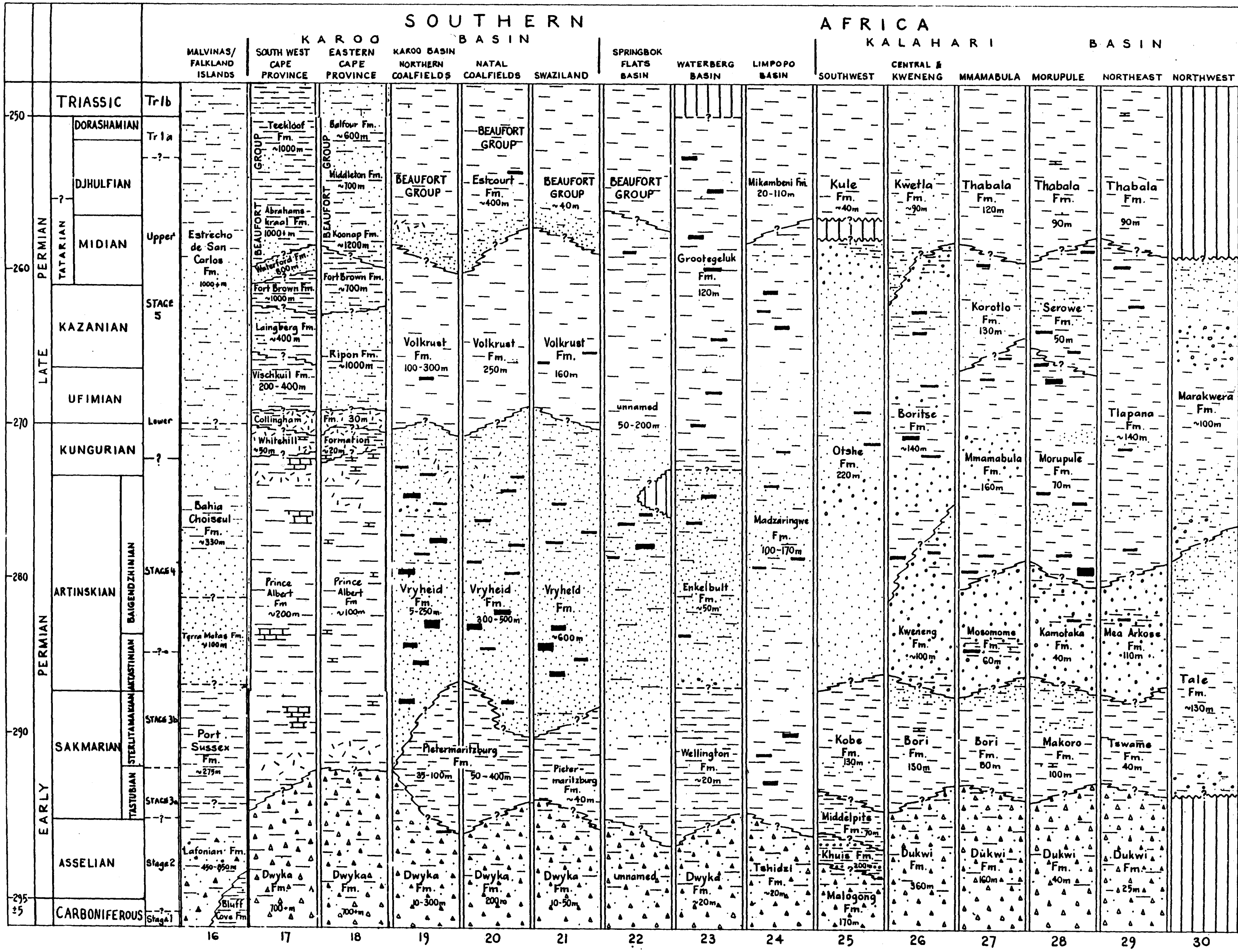

Figure 4. Stratigraphic Summary Columns (2)

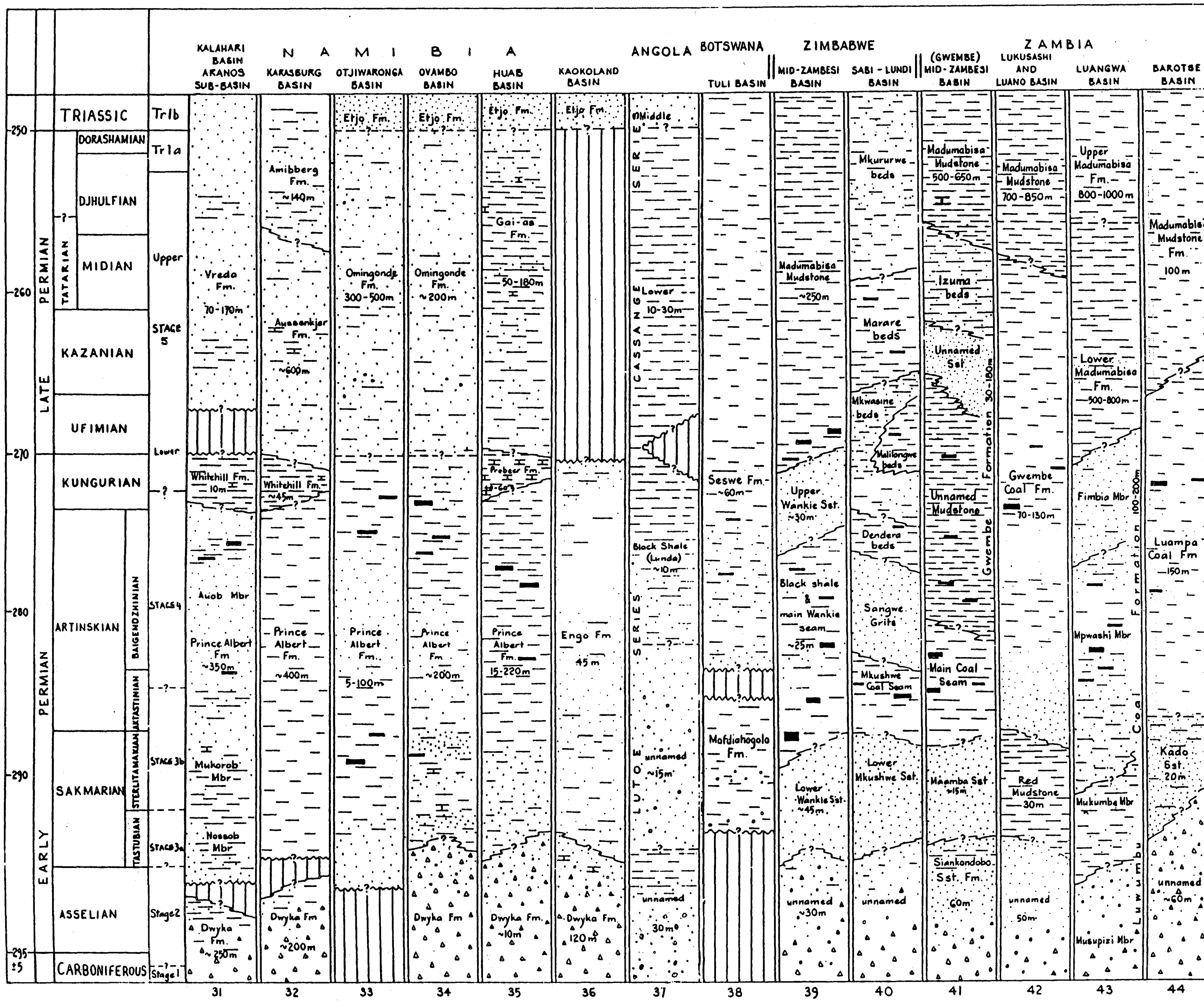

Figure 4. Stratigraphic Summary Columns (3)

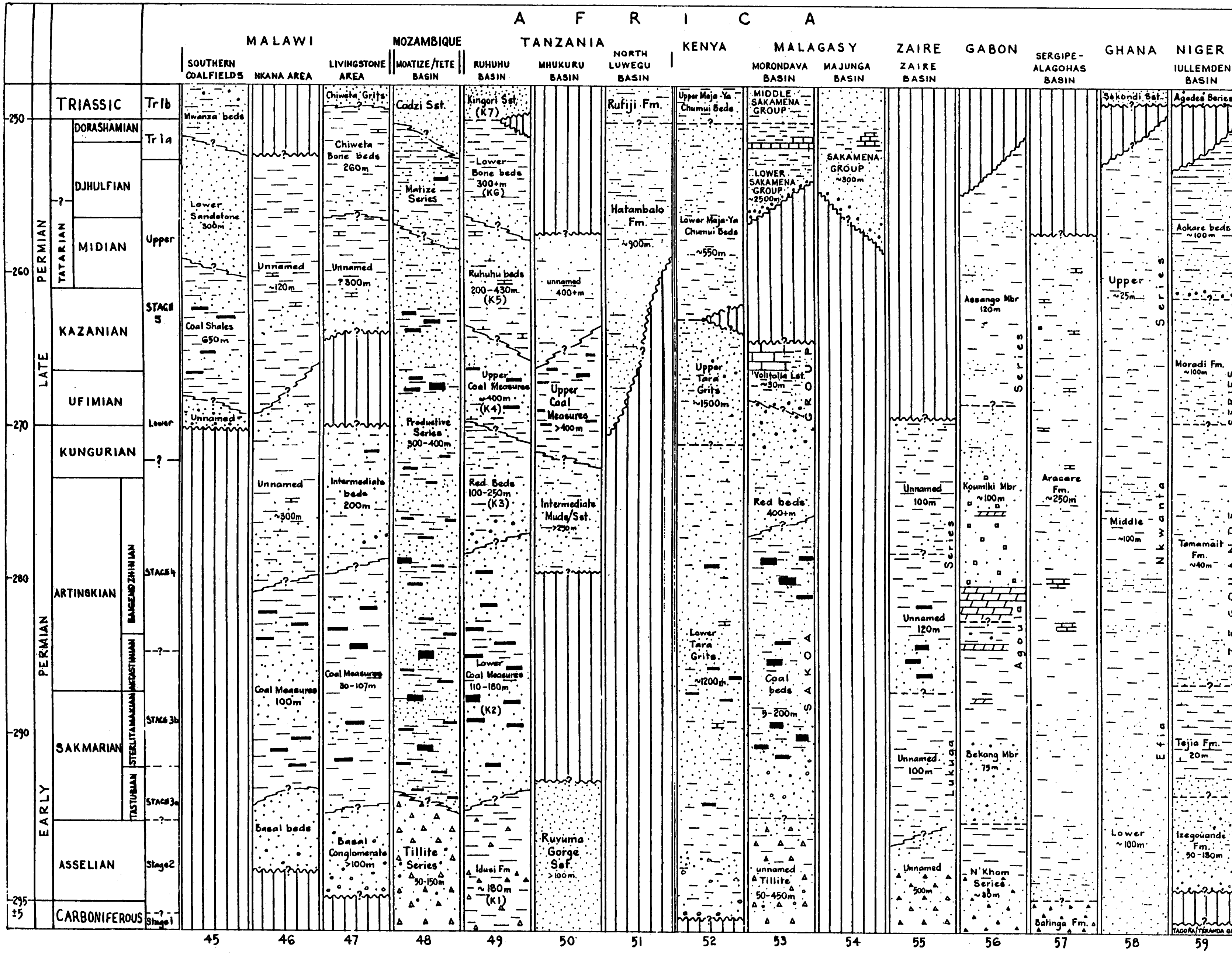

Figure 4. Stratigraphic Summary Columns (4)

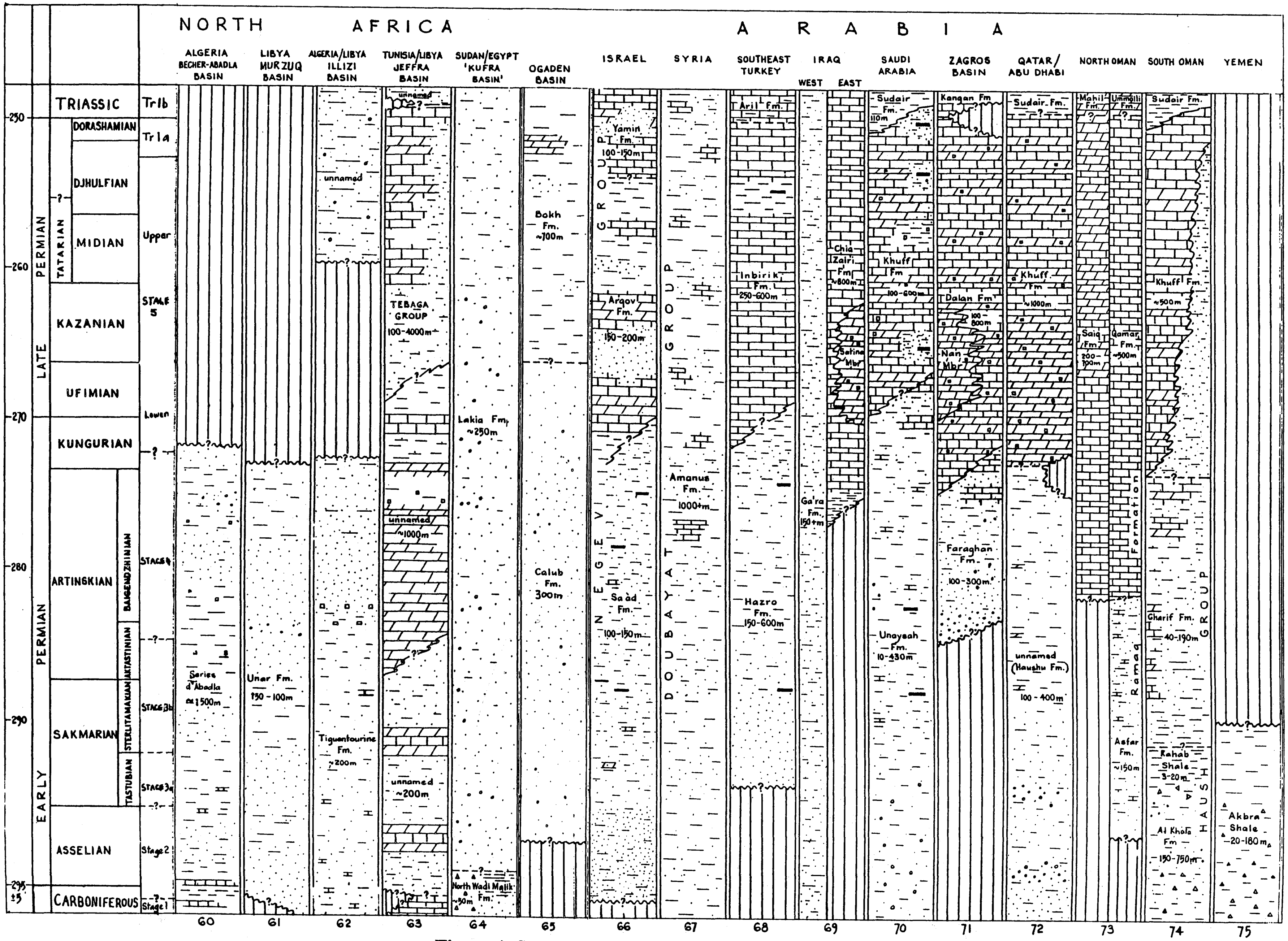

Figure 4. Stratigraphic Summary Columns (5)

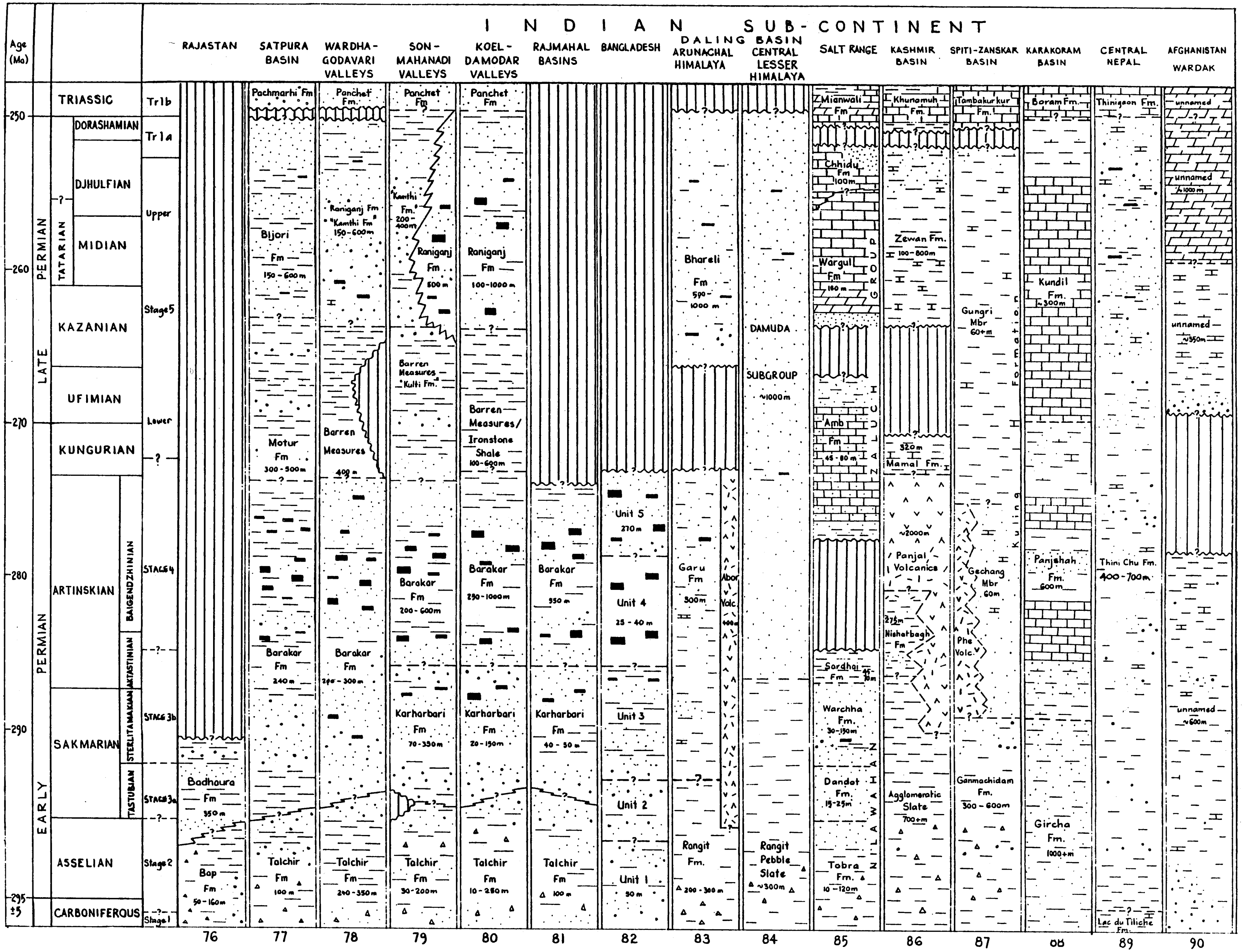

Figure 4. Stratigraphic Summary Columns (6)

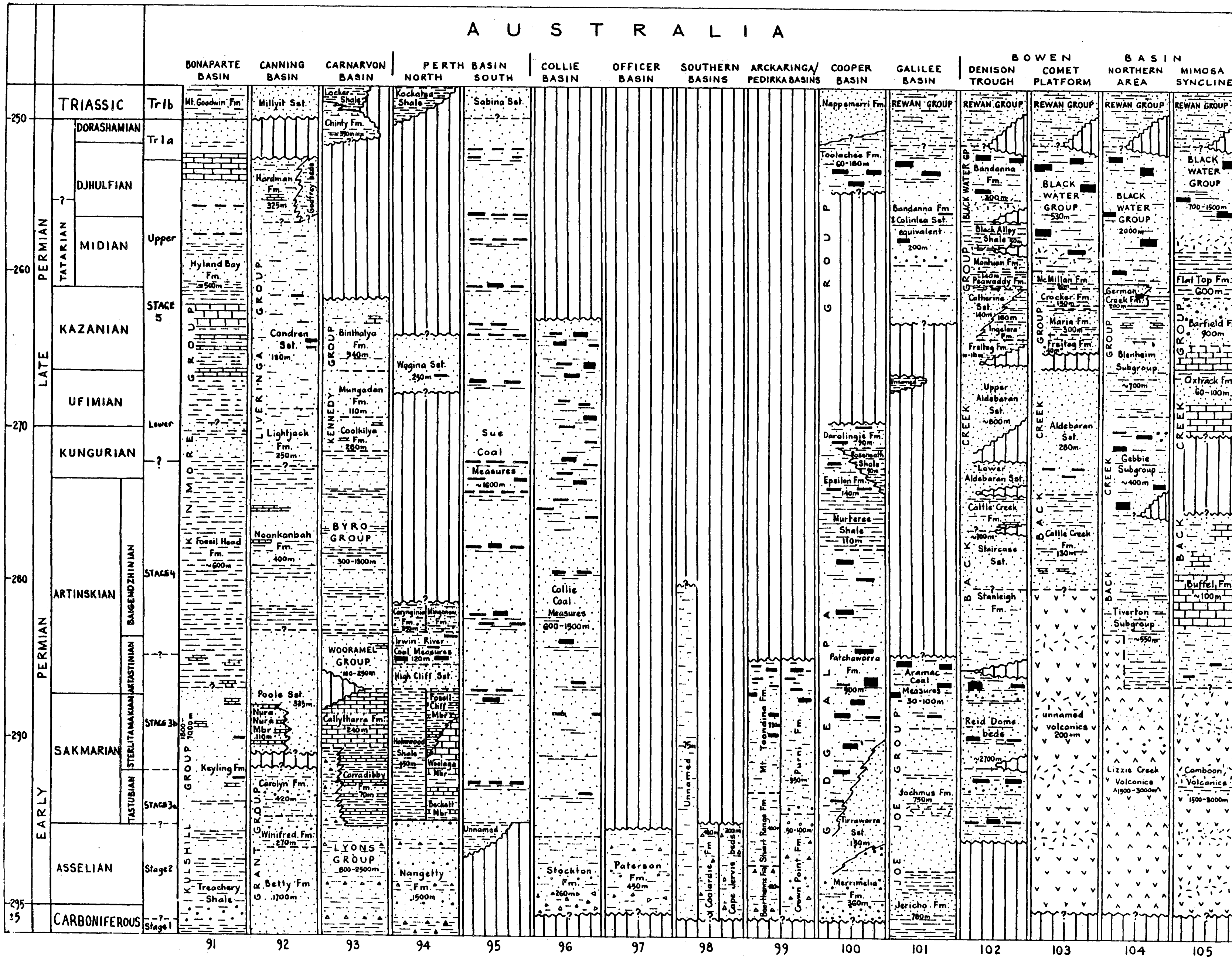

Figure 4. Stratigraphic Summary Columns (7)

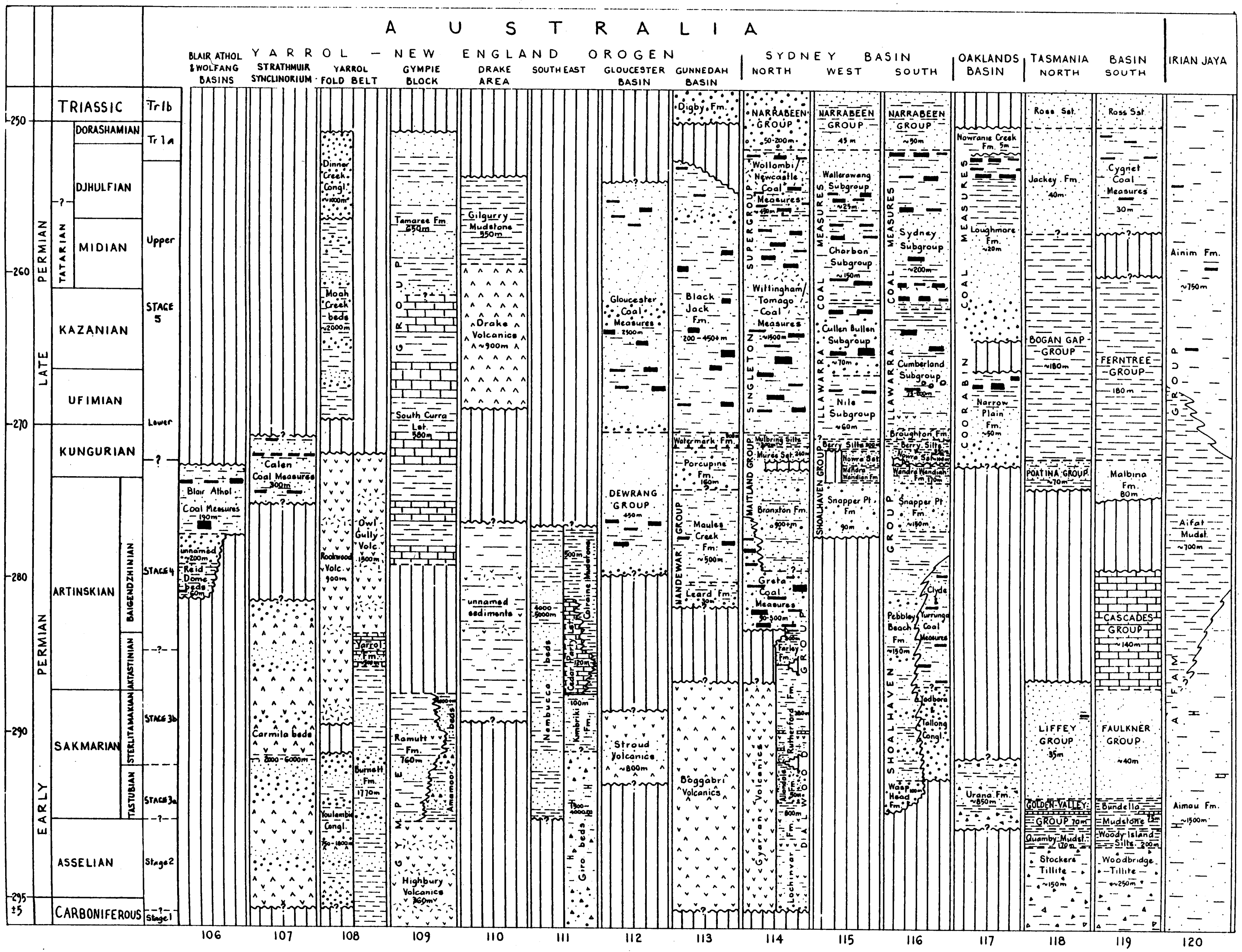

Figure 4. Stratigraphic Summary Columns (8)

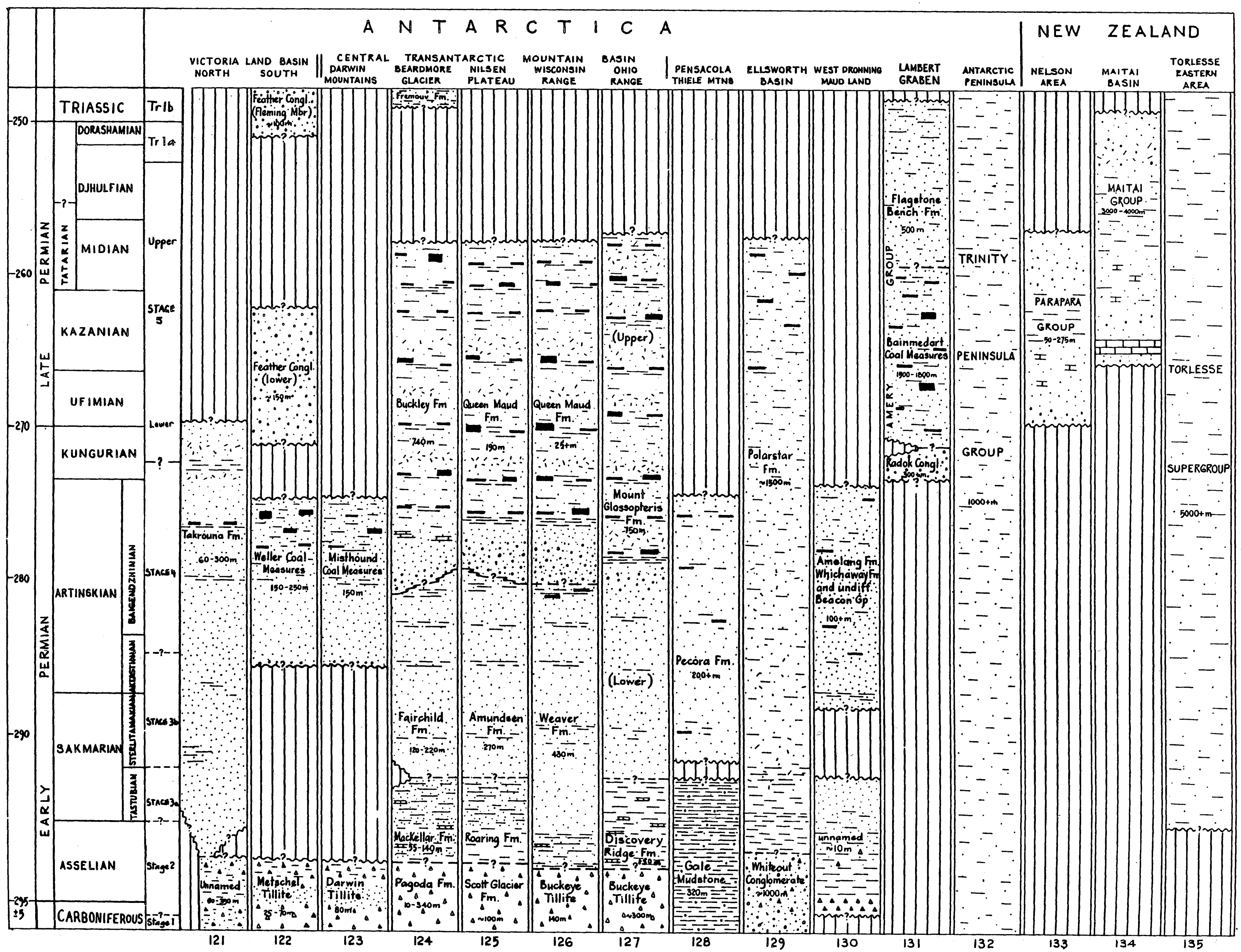

Figure 4. Stratigraphic Summary Columns (9)

(Plates 2-6) were compiled mainly from publically available information; Appendix 1 lists the major references used in compilation of the palaeogeographic maps.

PERMIAN TIMESCALE

Introduction

Several timescales are widely used for the Permian period, including those of Harland and others (1982), DNAG (Palmer 1983) and Menning (1988). Historically, the Permian timescale has been very poorly defined due to the lack of suitable and relatively complete successions in Western Europe. The proliferation of time-stratigraphic and rock-stratigraphic names from various parts of the world has also hampered the development of a universally accepted timescale (refer Logan & Hills, 1973). The timescale used in this study (Fig. 1) is taken from the Archbold & Dickens (1991) scale which has been developed for the Permian of Australia. A two-fold division of the Permian sequence into Early and Late Permian is commonly adopted and is further subdivided into several widely recognised stratigraphic stages.

The majority of the Permian stages are based upon Tethyan and low latitude marine successions in the southern United States, Asia and the Ural Mountains and Russian Platform. Ammonoids, fusulinids, conodonts, brachiopods and mollusc faunas are principally used for age determinations of Permian sequences. There is continuing debate on the suitabilty of the various stages for international correlation due to the absence or provinciality of many of the fauna and floras used, as well as the lack of reliable isotopic dates in many parts of the world. The Russian stage names have been adopted for the Australian successions, and can be broadly applied to other Gondwana continents. Although the high latitude position of much of Gondwana during the Permian, and the largely terrestrial nature of many of the Gondwanan sequences has resulted in a poor understanding of the age of many of the Gondwanan successions.

Geochronology

The chronostratigraphic scheme for the Permian period is constantly being revised and is currently considered to range from 295±5 Ma to 250±5 Ma. The radiometric data used to calibrate the duration of the Permian are derived from igneous rocks in Australia and to a lesser extent from South America and north-west Europe; i.e. volcanic and plutonic rocks in eastern Australia, western South America, Scotland, Germany and Norway (Forster & Warrington 1985). The absolute age of the Permian is still not well constrained; recent studies indicate that the Permo-Carboniferous boundary is approximately 298 Ma (Young, 1991)

Biochronology

A biostratigraphic chart (Fig. 1) depicting various biostratigraphic schemes applicable to Gondwanan sequences was compiled from numerous sources, and tied to the timescale of Archbold & Dickens (1991). The chart contains mainly floral zones as most Permian Gondwanan sequences are predominantly terrestrial or restricted marine facies.

Faunal zones:

A discussion of the Permian biostratigraphy of faunal schemes is beyond the scope of this study, however patterns of Boreal, Tethyan and Gondwanan realms are readily distinguishable and are critical in understanding Permian palaeogeography. Faunal provinciality (Fig. 5) has also been recognised within the Gondwanan realm; Andean, Paratinan, Austrazean, Westralian and Cimmerian provinces have been identified on genus distribution and species diversity (Archbold, 1983). Brachiopods and molluscs are the main faunas used in biostratigraphic correlation of marine sequences in Gondwana, whereas fusilinids are the principle faunas used for correlation along the Tethyan margin.

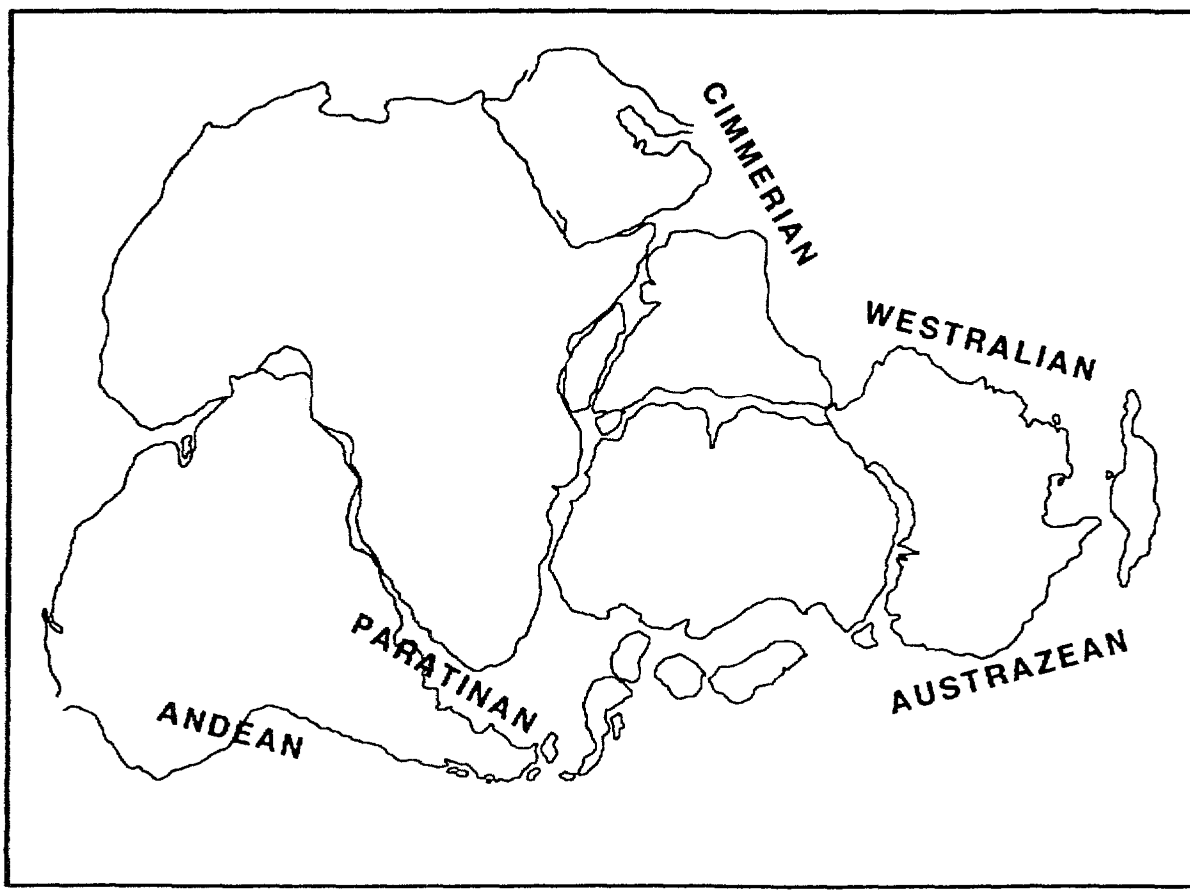

Figure 5. Faunal Provinces in Gondwana (Modified from Archbold, 1983)

Floral zones:

Distinct phytogeographic provinces within global Permian sequences have been recognised for over a century, and continuing work is conducted on the limits and characteristics of these provinces. Several species are common in different provinces, especially on the margins of regions and the degree of morphological similarity increases the closer the localities and climatic conditions.

The Permian Gondwanan, Angaran, Euroamerican and Cathaysian floral realms, resulted from an increased pole-to-equator temperature gradient that developed in the Carboniferous. The Gondwanan and Angaran realms generally represent cool to cold temperate high latitudes and the Euroamerican and Cathaysian realms generally represent mid-low latitude desert to tropical environments. Floral barriers were established by two large desert regions along the northern-western margin of Gondwana and in the Western United States and northern Europe, and to a lesser extent by seaways. Within each realm several biomes, homogenous vegetative systems, developed in response to latitudinal differentiation, similar to processes operating in the present world (Ziegler, 1990).

The last thirty years have seen an emergence of new or modified palynostratigraphic schemes based on both assemblage zones and/or interval zones for Late Carboniferous - Permian sequences on the major, now dispersed continents of Gondwana (Hart, 1967; Anderson, 1977, 1980; Truswell, 1980; Falcon,1975, 1984; Archangelsky & Azcuy, 1985; and Macrae, 1988). Inter-regional correlation based on these zones is, for the most part of a broad kind, however relatively high resolution correlation is now possible between certain intervals in various regions of Gondwana, for example, *Granulatisporites confluens* zone - Mid to Late Asselian (Foster & Waterhouse, 1988).

Data now available suggests that there was a differentiation of palaeofloras into a west and east Gondwana type. This distinction was more apparent in the latter part of the Permian, when the influence of glaciation had waned (Truswell, 1980). As a generalisation, it appears that eastern Gondwana had a greater diversity of pteridophyte spores (seed-ferns) than western Gondwana, where a greater morphological diversity of gymnosperm pollens is observed. As might be expected, important elements of European Permian floras are more pronounced in the west and Cathaysian floras are present along the Tethyan margin. Floral migration of various floral elements eg. *Lueckisporites* spp. and *Guttulapollenites* spp. between Gondwanan continents has also been recorded (Wood and others, 1991).

Provincialism has been recognised within southwest Gondwana in southern South America (Cuneo & Andreis, 1983; Cuneo, 1989). Three provinces have been defined including the Chacoparanan and Paganzo/Precordilleran, which are closely related to the Gondwanan floral realm, and a region of subtropical high diversity (Patagonian) that includes elements of Euroamerican flora. These provinces contain several subprovinces that reflect variation in palaeotopography and palaeoenvironments.

Saccate pollen assemblages provide a useful index for illustrating the floral changes that occurred during the Permian in Gondwana. The saccate pollen are derived from parent floras that represent relatively stable, upland or climax vegetation, i.e. plants that are less affected by variations in water level, as opposed to the the shoreline or lowland spore-producing flora. Major changes to the morphology of the pollen structures (striate and sulcate pollen structures) from the Early Permian to Late Permian suggest that such modifications represent protection against dessication as the climate changes from glacial to warm temperature in central Gondwana (Falcon, 1986).

PERMIAN CLIMATE AND FLORA IN GONDWANA

Climate

The Gondwanan supercontinent extended from the equator to the polar region during the Permian and was influenced by a highly differentiated climate that ranged from glacial, cold temperate, cool temperate, warm temperate and arid to subtropical. Following the extensive latest Carboniferous-earliest Permian glaciation, the climate in the Early Permian was dominated by the amelioration of conditions, coupled with relative high sea level and humid conditions. The western region of Gondwana i.e. northern South America, North Africa and Arabia were located in warm temperate, semi-arid, arid to subtropical climatic zones throughout the Permian. In contrast, the central and eastern regions of Gondwana lay within the warm temperate-cool temperate-cold temperate and glacial zones throughout the Early Permian, and rotated into warm temperate to cool temperate zones during the Late Permian. Continentality increased considerably from the Early to Late Permian, which was in part due to the relative lowering of sea level in many regions of Gondwana.

The global palaeoclimate of the Permian is considered to have been dominated by monsoonal atmospheric circulation due to the circum-equatorial oceanic circulation that resulted from the configuration of the Pangaean megacontinent (Parrish & Barron, 1986; Parrish and others, 1986). That is, the position (extending from the north to the south pole) and large size of the Pangaea caused the surface air pressure to deviate strongly from the zonal pattern that was developed over the ocean. Land areas respond more strongly to seasonal changes in solar radiation, due to their ability to absorb and radiate heat more effectively than water. The large Pangaean megacontinent became warm in summer, establishing a low pressure cell (ascending air), and cool in winter, probably developing a high pressure cell (descending air), which resulted in increased seasonality (i.e. monsoonal climate).

This effect was greatest during the Late Permian-Triassic when global plate movements caused the land area to be almost symmetrically disposed around the equator. As large areas of Gondwana were located in polar regions during the Permian the effect of the monsoonal atmospheric climate was probably considerably less than in mid to low latitudes.

Flora

Floral evidence suggests that *Botrychiopsis* floral assemblage, possibly equivalent to a tundra type vegetation, was present in ice-free areas during the Late Palaeozoic glaciation of Gondwana. It has been suggested that the *Potonieisporites* pollen assemblages are possibly derived from the primitive *Botrychiopsis* flora (Retallack, 1980). This flora was followed by an undetermined gymnosperm flora represented by monosaccate microflora, which appears to be similar to the taiga or conifer dominated flora that is present in the sub-arctic boreal regions of the present day northern hemisphere. These woodlands may have been accompanied by reed floras (articulates), growing in open areas or along the shores of rivers and deltas; the climate appears to have been too harsh to support herbaceous plants (Retallack, 1980; Falcon, 1986). The fact that some plants survived through the glacial period also suggests that such refuges did exist, and consequently a continous ice sheet covering the entire central Gondwanan region may not have existed. This is also supported by the occurrence of thin carbonaceous beds within diamictite sequences in the Parana, Mid-Zambezi and Karoo Basins as well as mega- and microfloras preserved within the Talchir Formation in peninsula India (Martini & Rochas-Campos; 1988, Falcon, 1975, 1986; Visser, 1989; Chandra & Chandra, 1987 and B. Cairncross, pers. comm.)

The *Botrychiopsis* and gymnosperm-type floras were replaced by new plants following the glacial maxima during the Asselian, as the temperature in Gondwana began to increase. Early Permian vegetation was composed mainly of gymnosperms that were dominated by pteridosperms (seed ferns), particularly the glossopterids, and pteridophytes (true ferns). The first arborescent floras to appear were the stunted *Gangamopteris* flora, which had oval-shaped leaves, and early conifers. These plants probably grew in gentler coastal climates, later penetrating inland; forests developed that have been compared to the birch-dominated taiga in the present day northern hemisphere. The *Glossopteris* flora probably evolved as part of the Gondwanan vegetation during the Sakmarian, however this could not have begun until permafrost conditions had ceased. *Glossopteris* had large aeration chambers in its root structure, which allowed growth in water-logged and acidic swamps and would have split apart if frozen (Gould, 1975; Retallack,1980).

In the mid Early Permian, the taiga dominated forests began to be replaced by extremely diversified and mixed *Glossopteris-Gangamopteris* dominated swamp forests. Detailed studies on early Permian swamps in the Bowen Basin (Draper & Beeston, 1985) suggest that the *Glossopteris-Gangamopteris floras* probably grew on levee banks and abandoned channels. The trunks of <u>some</u> *Glossopteris* species are up to 50cm across and therefore formed large trees that were adapted for growth in waterlogged conditions; its leaves were tongue-shaped, up to 20cm in length with a characteristic network of veins. Preserved autumnal banks of leaves indicate that *Glossopteris* was a deciduous tree (Retallack,1980). Pteridophytes, ferns, club-mosses and lycopods, horsetails and early gymnosperms formed the understory of the forests (Falcon, 1986) and articulates dominated the open swamps.

Glossopteris dominated the coal swamps during the Late Permian, however other trees were present including conifers, which occur in some diversity at the top of the coal seams. Many trees show annual growth rings clearly reflecting strongly seasonal climate. Conifers, for example *Walkomiella,* may well have dominated the upland and non-depositional areas beyond the basinal regions and coastal plains, possibly equivalent to the boreal conifer forests of the present world (Retallack, 1980; Zeigler, 1990). In the Late Permian, high diversity *Glossopteris* dominated coal swamps in Australia and India appeared to have occured as thick, dense forests with intervening floodplains and lakes; *Glossopteris* disappeared from floral assemblages at the end of the Permian and were replaced by conifers, which dominated the Triassic. The floral assemblages in the Upper Permian Raniganj Formation in India have been interpreted as indicating warm, humid temperate climate whereas equivalent units in eastern Australia are generally regarded as representing humid, cool to cold temperate conditions (Chandra & Chandra, 1987; Rigby, 1971)

The floral remains in central Gondwana, for example those in the Karoo sequences in Africa, suggest that the latest Permian climax vegetation in the region was dominated by high order plants (gymnosperms, or pteridosperms), with lower proportions of lower order spore-producing ferns, horsetails, etc. that require water for reproduction. The vegetation was possibly similar to that of a savannah-type system resulting from high temperature, seasonal climate similar to conditions that exist in mid-continent Africa and in middle latitudes of the present day world, (Falcon, 1986).

TECTONIC SETTING

Pangaea was largely assembled in the Permian, as a result of Late Palaeozoic continental collision between Gondwana and Laurussia and between Laurussia, Kazakhstania and Siberia (Fig. 6). A number of Asian microcontinents in the Tethyan seaway and terranes in the palaeo-Pacific Ocean (Panthalassa) remained separate from Pangaea (Ziegler, 1990; Nie and others, 1990; Stevens & Rycerski, 1983; Ross & Ross,1983).

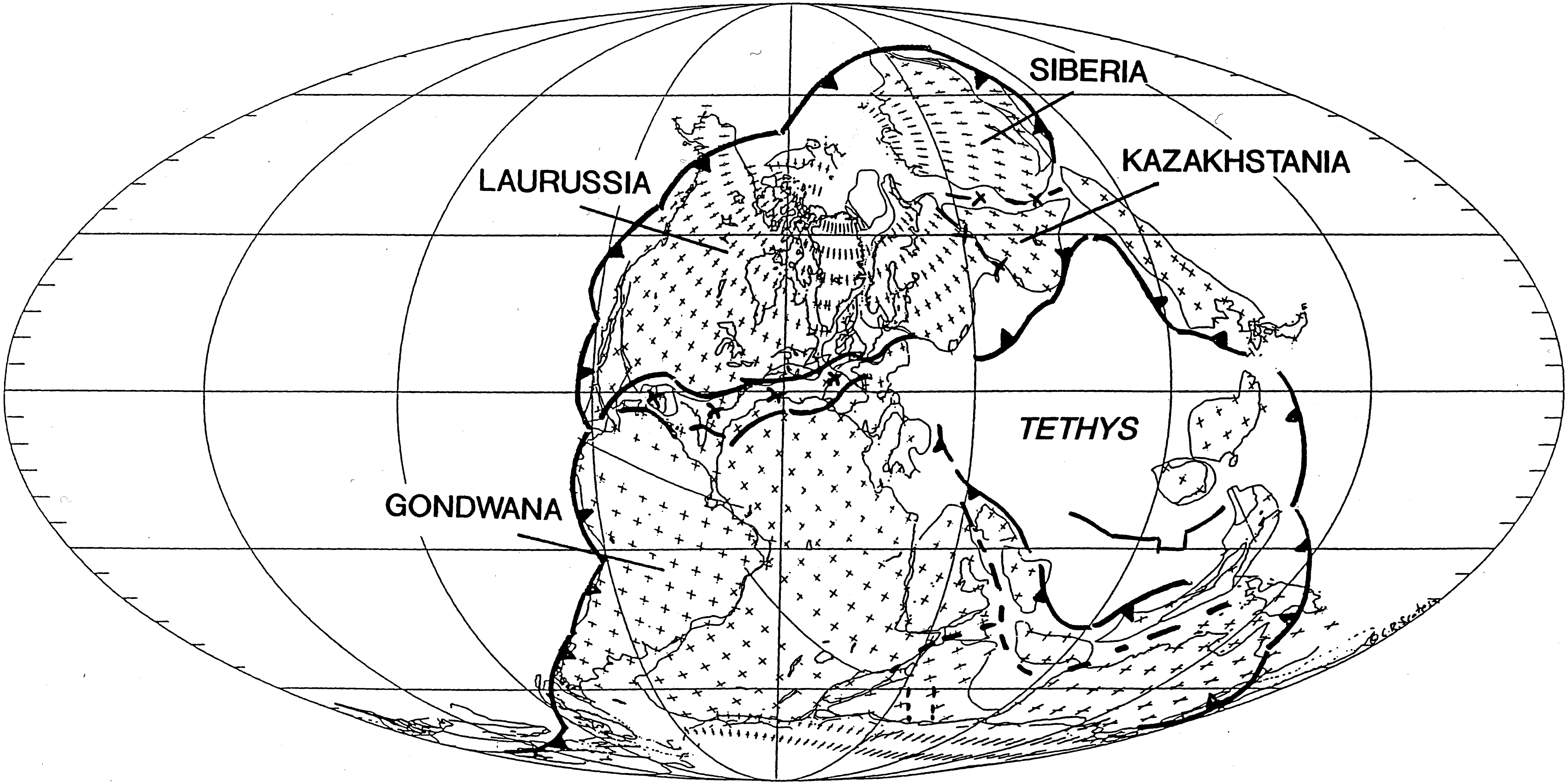

Figure 6. Global plate tectonic setting (Modified from Scotese, 1990)

During the Permian, the relative movement between Gondwana and Laurasia changed from mid Carboniferous-Early Permian suturing, which resulted in the formation of Pangaea, to Late Permian-Triassic extension, which led to the break-up of Pangaea and Gondwana, and the initial formation of the Atlantic and Neo-Tethys Oceans. There were changes in tectonic regimes from the Early to Late Permian in many regions of Gondwana, probably reflecting global changes in relative plate motions (Ziegler, 1988b). Extensional zones within the Gondwanan supercontinent (discussed in the following section) reflect the inherent instability of the supercontinent during the Permian.

The tectonic setting in Gondwana (Fig. 7) during the Permian can be divided into several regions: dominantly convergent settings along the southern and northwestern margins; a divergent margin along the northeastern margin; extensional regimes between east and west Gondwana (Malagasy Trough) and between Greater India and western Australia; and areas of intracratonic rifts and sags that generally occur in regions of pre-existing structural weaknesses, such as in peninsula India and southern Africa. An extensive glaciation during the Late Carboniferous to Early Permian loaded the crust with ice producing widescale isostatic movements.

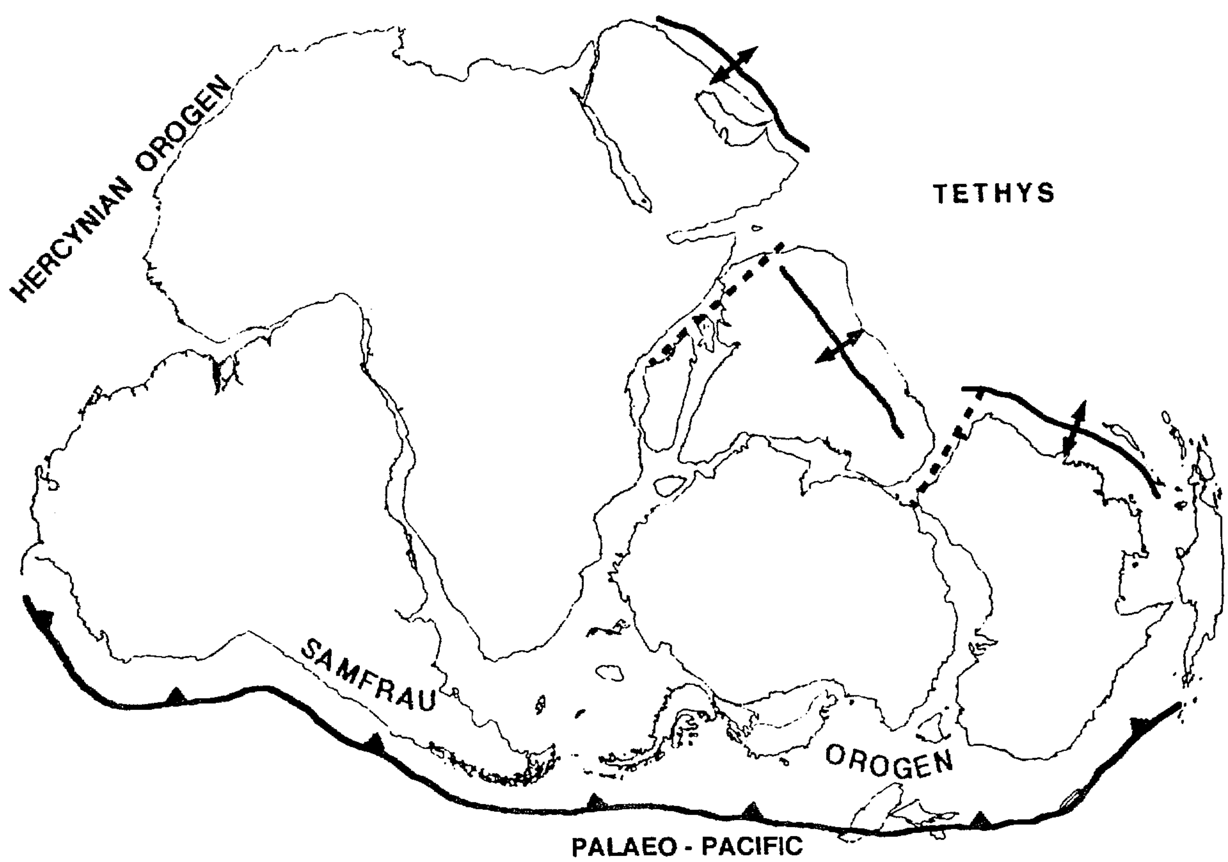

Figure 7. Permian tectonic settings in Gondwana

Southern Region

The southern margin of Gondwana, i.e. western and southern South America, western Antarctica and eastern Australia consists of a complex collage of lithospheric blocks that have collided and amalgamated to form the Late Precambrian to Mesozoic Samfrau Geosyncline (du Toit 1937). The margin represents a convergent continental margin between Gondwana and the palaeo-Pacific ocean during the late Palaeozoic; Permian magmatic arcs, back-arc and fore-arc basins and subduction zones have been recognised along the margin. Tectonic activity has been in part related to collision of terranes, for example, the Madre de Dois region in southern South America, areas of the New England Orogen in eastern Australia and in New Zealand, and possibly Patagonia.

The structural history of the extensive and long lived margin has long been the subject of conjecture and debate and reflects the complex nature of the accreted margin (Coney, 1990). Tectonic processes such as back-arc rifting, folding and thrusting, transcurrent faulting and magmatic activity, varied along the margin and a simple orthogonal subduction of the palaeo-Pacific Ocean under the Gondwanan craton is an unlikely scenario. The term *Gondwanide orogeny* was introduced by du Toit (1937) to describe a Permo-Triassic deformation event widely recognised along the southern Gondwanan margin. The extent, age and duration of this event varies along the margin and a continuous fold belt probably did not exist along the entire length of the margin. Deformation associated with the orogeny resulted in a complex arrangement of fold belts that reflect the nature of the margin during the Late Palaeozoic (Storey and others, 1987). Late Palaeozoic-Triassic strike-slip movements have also been recognised in many regions along the southern orogenic margin of Gondwana.

Northwestern Region

Palaeomagnetic and other studies (Scotese, 1984; Scotese and others, 1979; Lefort, 1989; Dallmeyer, 1989; Zeigler, 1988a,b) indicate that Gondwana moved northwards during the Late Palaeozoic and collided with North America and southern Europe in the mid Carboniferous-Permian (the Hercynian orogeny). The convergence and suturing of Gondwana and Laurasia, resulted in both shortening and strike-slip movement and the formation of a complex system of fold belts that include the Variscan, Alleghanian, Mautianide, and Ouachita orogenic belts (Ziegler, 1988a,b; Lefort, 1989; Ross, 1986; Dallmeyer & Villeneuve, 1987; Veile & Thomas, 1989). The suture between Gondwana and Laurentia is not exposed at the surface and its location is based on geophysical, stratigraphic and structural data (Rowley & Pindell, 1989; Dallmeyer, 1989).

The early to mid Palaeozoic oceanic pelagic and turbidite deposits between the continents were incorporated into large accretionary wedges that formed highlands on the cratonic margin of North

America. Continual loading of the crust formed a series of foredeeps (Permian basins in the southern United States), immediately north and west of the Marathon and Ouachita allochthonous orogens. The joining of the two continents was essentially completed by the Early Permian (Ross, 1986; Veile & Thomas, 1989).

The tectonic setting at the confluence of the northern Andean orogen and the Gulf of Mexico/Caribbean region is poorly understood; a collage of terranes, including the Yucatan Terrane, were probably present in the area. Pindell and Dewey (1982) have proposed that a Late Palaeozoic arc was present in Columbia and Venezuela and subduction of oceanic crust occurred beneath the northwestern and western margin of South America. Transcurrent faulting along the margin (Restrepo & Toussaint, 1989) has also been envoked to explain the accretion of terranes in the region.

Northeastern Region (Tethyan margin)

The northern Tethyan margin of Gondwana stretched from Tunisia in North Africa in the west, to Timor and Irian Jaya in the east. An assemblage of microcontinents (terranes) were present along the southern margin of the Tethyan ocean (Palaeo-Tethys); many of these microcontinents contain lithological and biological elements common to both Gondwana and Tethys (discussed later). Localised volcanic activity, increased subsidence rates and other evidence (Metcalfe, 1988; Smith, 1988; Sengör and others, 1988; Nie and others, 1990) indicate that most of the southern belt of Tethyan microcontinents rifted from the Gondwanan margin during the Permian and Triassic. This rifting initiated the formation of the Neo-Tethys ocean between the microcontinents and Gondwana.

STRUCTURAL AND STRATIGRAPHIC FRAMEWORK OF PERMIAN GONDWANAN SUCCESSIONS

The following section gives a brief summary of the structural setting and stratigraphy of Permian successions in basins and orogenic regions throughout Gondwana. Most of the sequences are illustrated in the summary stratigraphic columns (Figure 4 (1-9)), with locations shown in Figure 3 and Plate 1. Most of the sequences described in the following section have an accompanying stratigraphic column, and where applicable, a stratigraphic column reference number, in brackets, is given.

AUSTRALIAN REGION

Permian successions are preserved throughout the Australian region in a variety of structural settings. The region has been divided into several areas that contain either comparable sequences or similar tectonic settings. These include basins along the north and northwest margin basins that were formed by extensional processes in the Late Carboniferous-Early Permian and contain thick Permian sequences; the intracratonic basins where subsidence was related to reactivation of pre-existing structures; and the extensive basin system bordering the orogenic belt in eastern Australia, which was probably formed by back-arc extension in the Early Permian but became a foreland basin during mid-Late Permian compression.

NORTHERN AREA

Arafura Basin

Lower Permian sediments have been intersected in two wells in the Goulburn Graben of the Palaeozoic to Early Mesozoic Arafura Basin (McLennan & others 1991; Bradshaw & others, 1991), although on seismic evidence Permian sediments appear more widespread. The structural origin of the basin is not well understood although evidence from seismic data indicates possible transtensional movement within the basin during the latest Carboniferous-Early Permian; this is supported by a K/Ar date of 293±3 Ma on a dolerite sill. This activity may have been related to rifting of Sibumasu from the edge of Gondwana in the late Early Permian (Metcalfe, 1988)

Timor

A sequence of Early Permian and Triassic fine grained clastics and minor carbonates, separated by a depositional hiatus, has been mapped in western Timor (Bird and others, 1987). These sediments appear to have been deposited in an intra-cratonic basin that underwent periodic northwest-southeast orientated extension. Provenance studies indicate that the source of the sediments lay to the north of the Australian craton in contrast to sediments on the Northwest Shelf that were sourced from the Australian hinterland. The hiatus between the Early Permian and the Triassic successions may represent a rifting episode that removed continental fragments (parts of South-East Asia) from the Australian northwest margin during the ?mid Permian (Metcalfe, 1988). Early and Late Permian fossiliferous sediments, including carbonates, are also present in Timor, where they occur as allochtonous blocks within younger material. The tectonic setting of these fossiliferous setting is uncertain (Archbold and others, 1982)

Irian Jaya shelf (120)

Permian shallow marine and fluvial-deltaic, coal bearing sediments are present in the Central Range of Irian Jaya and in the para-autochthonous and allochthonous "Birds Head" region to west. Widespread marine conditions in the region during the Early Permian (Archbold and others, 1982) were replaced later in the Permian by paralic, alluvial and restricted peat swamp conditions. The Permian sediments in the folded Central Range probably continue southwards into the Arafura Sea area (Pigram & Panggabean, 1983).

NORTH WEST SHELF

The North West Shelf region of Australia encompasses a number of present day offshore basins, including the Bonaparte, Browse, Canning, and Carnarvon Basins, which contain Late Palaeozoic to Cenozoic sediments; some of the basins extend onshore. Early extensional movements occurred in the basins during the Late Palaeozoic. This is possibly responsible for the regional northeast structural trend of the Mesozoic basins on the North West Shelf. The offshore Early Permian sequence is poorly known due to lack of drilling, although the Late Permian has been intersected in several wells closer to shore, and there is some seismic information on the Late Palaeozoic sequences.

Bonaparte Basin (91)

The Bonaparte Basin contains a thick (over 6000 m) and possibly complete section of Permian succession. Late Palaeozoic fault activity in the basin is evident in both the present day onshore and offshore parts of the basin (Mory,1988; Veevers & Roberts, 1968), and is probably due to reactivation of pre-existing faults during extensional tectonism along the western margin of the Australian craton. Gas reservoirs are present in deltaic Late Permian sediments of the Hyland Bay Formation.

Browse Basin

Seismic and drilling evidence suggests that up to 4000 metres of Carboniferous-Permian sediments are present in the basin that were deposited in an extensional regime at the end of the Carboniferous (Allen & others, 1978) and in the Late Permian (Powell, 1976). The Permian section is not well known.

Canning Basin (92)

The distribution of offshore Permian sediments is poorly known. Basin-wide subsidence and faulting occurred in the Canning Basin from the Late Carboniferous to the Late Triassic, although during the Late Permian sedimentation was confined to the onshore, Fitzroy Trough region. Mafic intrusions of tholeiitic affinity are present in the northwestern part of the basin. The intrusions are probably of Permian-Triassic age (Reeckmann & Mebberson, 1984), and are similar to intrusions in the northern

Carnarvon Basin. This igneous activity was probably related to rifting along the northwest margin during the Permian.

Carnarvon Basin (93)

The Silurian to Tertiary Carnarvon basin contains over 3500 metres of Upper Carboniferous to Permian sediments. Uplift of the eastern cratonic margin (possibly glacially induced) during the Early Permian produced a north-south orientated trough and local fault movement at the southern end of the basin formed two major sub-basins. Mid to Late Permian regional uplift, faulting and folding within the basin has been recognised (Moore and others, 1980a,b; Hocking & others,1987; Kopsen & McGann (1985).

INTERIOR BASINS

Perth Basin (94, 95)

The structural style and stratigraphy of the Perth Basin varies from the north to the south. Marine conditions were established in the northern part of the basin early in the Permian coincident with low-angle extensional faulting, whereas fluvial coal measures accumulated throughout most of the Permian in a meridionally orientated graben in the south. Recent studies (Marshall & Lee,1987), have proposed that east-west orientated extensional phases in the northern part of the basin during the Early and early Late Permian were associated with transtensional movements along major faults zones. Sedimentation probably extended eastward of the active, bounding Darling Fault and has been subsequently eroded. Local Permian faulting in a number of small basins to the east (including the Collie Basin) has preserved some of the Permian sediments. Undersaturated alkali volcanics are present in the northern part of the basin and have been dated as 267±5Ma (K-Ar) (Le Maitre, 1975). Similar volcanic rocks have been identified in extensional regimes on present day continental margins.

Collie Basin (96)

The Collie Basin is one of three small intracratonic fault-bounded basins within the Precambian Yilgarn Block; two smaller basins to the south are the Wilga and Boyup Basins (Playford, 1976; Backhouse, 1990). The Collie Basin is a northwest orientated basin comprising two half grabens, with northwest-southeast faulted margins. Economic coal deposits within the basin are lateral equivalents of the Sue Coal Measures in the Perth Basin, indicating that the basins were probably contiguous during the Permian.

Officer Basin (97)

A thin veneer of flat-lying Permian glacigene rocks is preserved in the extensive Officer Basin. The basin appears to have been tectonically inactive during the Permian (Jackson & van de Graff, 1981).

Mallabie Trough, Polda Basin, Troubridge Basin (98)

The Mallabie Trough is a poorly known basin that contains fine grained, glacio-marine dominated Early Permian sediments. To the east, the Polda Basin is a long-lived, periodically active trough containing glacially derived Permian sediments that were preserved by east-west trending faults (Cooper & Gatehouse, 1983). A thin sequence of glacial sediments is preserved in the Troubridge Basin where syndepositional faulting has been identified (Foster, 1974), and may be related to early rifting between Australia and Antarctica (McGowran, 1973).

Arckaringa Basin, Pedirka Basin (99)

The arcuate Arckaringa Basin was the site of Late Carboniferous-Early Permian fault activity along prexisting zones of structural weakness that produced a series of grabens, depressions and structural highs. Glacial and post-glacial sediments, including coal measures, accumulated in the basin although the latter sediments appear to have been deposited during a less active tectonic regime.

The Pedirka Basin contains an equivalent Early Permian section. A phase of Early Permian extensional faulting in the basin is evident from seismic data (Moore, 1986). Deposition ceased in the Artinskian and the basin was affected by a period of Late Permian structuring.

Cooper Basin (100)

Earliest Permian extension formed a series of half-grabens and subsequent structural development was controlled by dextral strike-slip movements. The Cooper Basin contains up to 1000 metres of sediment including thick coal measures that are the source of oil and gas recovered from overlying Mesozoic reservoirs (Smyth & Cameron, 1982). High rank coals (anthracite and meta-anthracites) occur locally within the basin, which are possibly a result of high heat flow from underlying granites or vertical movements of hot fluids derived from deep within the basin or from the basement. Thermal blanketing due to rapid deposition of younger sediments has also been evoked as a cause for the high-rank coals (Middleton & Hunt, 1989). A regional hiatus is present in the basin between late Early to late Late Permian sediments; many faults show evidence of structural inversion at this time. A disruption to sedimentation during this interval is recognised in many other Gondwanan basins.

Galilee Basin (101)

The areally extensive but thin Upper Carboniferous to Middle Triassic Galilee Basin is continuous with the Bowen Basin to the east and probably connected with the Cooper Basin to the southwest. Major northeast trending structures within the underlying Palaeozoic basement were reactivaved during the Permian and were a major controlling factor in Permian sedimentation. Deposition was generally continuous from the Late Carboniferous to the mid Permian, with a break in sedimentation during the early Late Permian; coal measure sedimentation continued in the Late Permian (Day and others, 1983; Wells 1989a).

Murray Infrabasins, Oaklands Basin,

Permo-Carboniferous glacial, platform cover sediments are preserved beneath the Murray Basin in ?reactivated Devonian troughs (Brown & Stephenson, 1991). Further east, glacial sediments and Late Permian coal measures are preserved in the north-northeast trending Oaklands Basin. Syndepositional faulting has been observed within the glacial sediments and differential compaction and slow subsidence has preserved remnants of probably more extensive coal measure deposits (O'Brien, 1986).

Tasmania Basin (118, 119)

Upper Carboniferous to Upper Triassic sediments (Parmeener Supergroup) occur in the Tasmanian Basin, which covers the eastern part of the present day island. Deposition occurred mainly in a north to northwest trending trough, associated with minor fault activity that produced local facies changes, although most of the sequence is relatively undisturbed. The Permian succession consists of glacial sediments overlain by cold water, open marine clastics and carbonates, which in turn are overlain by an regressive fluvial sequence. Thin coal seams were deposited in both the early and latest Permian (Banks and Clarke, 1987; Burrett & Martin, 1988).

Olive River Basin, Laura Infrabasins, Mount Mulligan area

The Olive River Basin is a small intracratonic basin in northeastern Queensland which contains a thin, shallow westerly dipping, Carboniferous - Permian succession that includes coal measures. Fault activity on the western side of the basin may have influenced deposition, (Wells, 1984b). Permian paralic-fluvial sediments also occur in fault blocks in the Mesozoic Laura Basin (Wells, 1984d). Further south, in the Mount Mulligan region, a fault block contains Permo-Triassic conglomerates and coal measures, that were probably deposited in a small extensional basin (Wells, 1984c).

SYDNEY-GUNNEDAH-BOWEN BASINS

The Sydney-Gunnedah-Bowen Basin system forms an extensive trough, over 1500km in length, inboard of the New England Orogen. It has been proposed (Murray, 1985) that it developed as a retroarc foreland basin in response to crustal loading by a volcanic arc to the east. Other authors (Scheibner, 1973; Korsch, 1982; Mallet and others, 1988) believe it was initiated during a Late Carboniferous-Early Permian phase of back-arc extension, associated with a continental margin volcanic arc. Westwards directed thrusting to the east of the basins in the Late Permian marked the onset of foreland basin conditions.

Sydney Basin (114-116)

The Sydney Basin, which contains Early Permian to Mid Triassic sediments and volcanics, is bounded to the northeast by the Hunter-Mooki Fault System and is continuous with the Gunnedah Basin to the northwest. Its western and southern margins are erosional but approximate the depositional edge of the basin; the eastern margin continues to the continental shelf. The basin can be divided into a shelf region to the south and west and a series of active north trending troughs and ridges in the rest of the basin.

Bimodal volcanics and marine sediments occur at the base of the sequence, suggesting an extensional origin. They are overlain by Early Permian terrestrial to paralic coal measures, which are in turn overlain by marine sediments. The Late Permian sequence consists of fluvial or fluvio-deltaic coal measures with locally deposited tuffs and thin marine intervals. From the mid Permian the structural style of the basin changed to that of a foreland basin; uplift, folding and thrust faulting to the northeast (Hunter Orogeny), resulted in a regional regression and coal deposition (Greta Coal Measures). This regression was short lived and marine conditions prevailed over most of the basin, until the Late Permian when thick coal measures were deposited. Coal measure deposition was concomitant with further thrusting along the Hunter-Mooki fault, and widespread silicic volcanism, located to the north and northeast of the basin (Herbert & Helby, 1980; Hobday, 1987).

Gunnedah Basin (113)

The eastern boundary of the Gunnedah Basin is formed by the Hunter-Mooki Fault System; in the north, the basin appears to be continuous with the Taroom Trough of the Bowen Basin, and in the south is contiguous with the Sydney Basin. An Early Permian to Mid Triassic sequence similar to the northern Sydney Basin (bimodal volcanics overlain by fluvio-deltaic, marine and coal-bearing deltaic deposits) is preserved within the basin. Two major sub-basins in the northwest and southern part of the basin are separated from the eastern sub-basins by the northerly-trending Boggabi Ridge (Hamilton and others, 1989).

Bowen Basin (102-105)

The Bowen Basin is a north-south trending elongate basin with two main depocentres; the Denison Trough in the west and the asymmetric Taroom Trough in the east, which are separated by the Comet Platform; the Taroom Trough contains up to 10km of Permo-Triassic sediments (Dickens & Malone, 1973; Fielding and others, 1991). The western margin is bounded by cratonised Palaeozoic and Precambian basement and the eastern margin is bounded by the Yarrol Province (an intermittently active volcanic chain and intensely deformed fold belt), which is part of the New England Orogen (Day and others, 1983; Murray, 1985). Faults and fold axes in the basin generally trend north-south; some of the normal faults were reactivated during a compressional phase in the Late Permian and Triassic.

During an Early Permian extensional phase, coal-bearing non-marine sediments (Ried Dome Beds) were deposited in grabens and half-grabens in the Denison Trough; to the east a thick pile of volcanics and sediments derived from the Camboon Volcanic Arc accumulated. Extension was followed by a period of thermal sag, during which shallow and marginal marine sediments were deposited over most of the basin. The first indication of compression associated with the onset of foreland basin conditions was in the mid-Permian; the Aldebaran Sandstone deltas were a product of this tectonic activity. A further phase of thermal sag saw the widespread establishment of marine conditions.

During the Late Permian, sediments shed from the orogen to the east accumulated in alluvial plain, deltaic and paralic environments to form the extensive coal measures of the Blackwater Group and equivalents, coincident with a phase of calc-alkaline arc volcanism. In the latest Permian-Mid Triassic, the basin was subject to a period of intense compression with the partial inversion of basin sequences and the development of high-angle reverse faults (Ziolkowski & Taylor, 1985). Deposition of fluvial sediments (Rewan Group) began in the latest Permian and continued into the Mid-Triassic (Foster, 1979).

Coal rank in the Sydney-Gunnedah-Bowen Basins decreases markedly from east to west and appears to be mainly a result of burial depth, although magmatic intrusions locally increase coal rank. Structural complexity within the basins also parallels the overall coal rank trend (Diessel, 1975; Middleton & Hunt, 1989).

Blair Athol & Wolfgang Basins (106)

Small extensional basins located to the west of the Bowen Basin were the site of deposition of locally thick coal measure sequences (up to 40m thick seams) during the mid Permian. The coal seams generally have very low clastic and ash contents, suggesting that they accumulated as mounded peats or raised bogs, which received limited clastic material possibly due to elevated basin margins (Hobday, 1987).

Gloucester Basin (112)

The Gloucester Basin is a meridionally orientated trough in the southern part of the New England Orogen that was probably contiguous with the Sydney Basin to the south during its development. Lower Permian volcanics and sediments are unconformably overlain by paralic sediments including coal measures and Late Permian alluvial to lower delta plain coal measures (Lennox & Wilcox, 1985).

NEW ENGLAND OROGEN

The New England Orogen is an extremely complex feature composed of a series of troughs and grabens, plutonic and volcanic suites, fold and thrust belts, a major orocline structure and allochthonous blocks. During the Devonian-Carboniferous the New England Orogen was the site of an east- facing, Andean-type convergent margin, with ignimbritic volcanism in the arc and fore-arc and accretionary wedge deposition to the east. The Permian evolution of the New England Orogen is not well understood and is the subject of considerable debate; it is beyond the scope of this report to give a detailed account of various hypotheses that have been developed (see, for example: Flood & Runnegar, 1982; Day and others, 1983; Harrington, 1983; Murray, 1985; Murray and others, 1987; Korsch & Harrington, 1981; Korsch and others, 1991). The New England Orogen can be divided into a northern Yarrol Province, southern New England Province and the Gympie Province, which consists of a number of allochthonous terranes.

Yarrol Province (107, 108)

In the Early Permian, much of the Yarrol Province was a fore-arc basin to the Camboon Volcanic Arc. The Grantleigh Trough developed to the east of the arc in the Early Permian, possibly as a pull-apart basin (Murray and others, 1987); deep water turbidites and spilitic lavas were deposited in the trough. To the north, in the Strathmuir Synclinorium, distal andesitic volcanics from the Camboon Volcanic Arc were deposited; they are partly overlain by mid Permian marine sediments. These sediments were later folded into a broad synclinal feature, although the style of deformation varies within the trough.

The Yarrol Province underwent deformation during the mid Permian, with folding along north-northwest trending fold axes and reverse faulting. During the Late Permian-Early Triassic, deformation was renewed with further folding and reverse faulting. Deformation in the Yarrol Province was accompanied by metamorphism and the emplacement of granites and serpentinites; some of this deformation may have been related to terrane accretion.

Gympie Province (109)

The Carboniferous to Permian sequence in the Gympie region is composed of volcanics and sediments, including carbonates. The Gympie Province shows little evidence of the mid-Late Permian deformation that affected the Yarrol Province. It has been proposed that the Gympie Province is an allochthonous terrane with close similarities to island arc terranes in New Zealand (Harrington, 1983). The Gympie Block is probably composed of several allochthonous terranes with both island arc and continental margin affinities. These terranes may have docked with the Australian craton during the Middle Triassic, the subsequent deformation causing the cessation of sedimentation in the Bowen

Basin in eastern Australia (Harrington & Korsch, 1985). Other terranes have also been identified in the region, to the north and south of Gympie area.

New England Province (110, 111)

During the Carboniferous the New England Province was the site of an Andean-type convergent margin with a westerly dipping subduction zone. During the Late Carboniferous-Early Permian there was a change in tectonic regime from an oblique convergent margin to a dextral strike-slip margin (Murray and others, 1987). The province was then in an extensional, back-arc environment; the postulated arc apparently stepped eastwards and is represented by parts of the New Zealand and Gympie Terranes. A marginal basin developed in the New England Province behind the arc. This basin contains deep water turbidites and limited oceanic crust (Leitch, 1988). The dextral transcurrent margin produced a major orocline structure in the region with about 500 km of displacement; the timing of the orocline is conjectural and is either Late Carboniferous or Early to mid-Permian. It has been proposed that the controlling structure for the orocline was the Mooki Fault System and that movement took place on a crustal detachment surface on top of the previous subduction zone (Korsch & Harrington, 1987). The New England Province was subjected to three phases of deformation during the Permian and S-type granitoid intrusion in the Late Carboniferous-Early Permian. Widespread emplacement of I-type granitoids and explosive felsic volcanism accompanied a period of deformation in the Late Permian-Early Triassic.

NEW ZEALAND

New Zealand was located on the eastern margin of Gondwanaland and has a complex structural evolution. It consists of an older part (Western Province) where the basement is Ordovician or older (possibly Precambrian) and a younger part (Eastern Province) where the basement is no older than Carboniferous. The relationship of the Western Province to nearby Australia, Antarctica and adjoining platforms (Lord Howe Rise etc.) is poorly understood, however it is thought to be contiguous with the Tasman Geosyncline (Crook & Feary, 1982). The Eastern Province has been subdivided into six tectonostratigraphic units (Korsch & Wellman, 1988) that have been identified as various components of a Late Palaeozoic to Mesozoic subduction complex.

Western Province (133)

The cratonic western province contains a small outcrop of neritic to marginal marine Permian quartzose clastics of the Parapara Group. The marine fauna and lithofacies is similar to faunas found in Tasmania.

Eastern Province (134, 135)

Brook Street Magmatic Arc:

The Brook Street magmatic arc consist of a volcanic and related intrusive suite of tholeitic and andesitic igneous rocks that appear to represent two arc complexes (Williams and Smith, 1979). The andesitic arc is probably post-Permian in age, whereas the mafic volcanics range from Permian to middle Mesozoic.

Maitai - Murihiku Forearc Basin:

The Maitai part of the forearc unit, in the South Island, is mid to late Permian in age (Suggate et al,. 1978), and unconformably overlies, or is faulted against, the Dun Mountain Ophiolite. It is composed of volcanogenic siltstone (derived from the active magmatic arc to the west) and turbiditic clastics and carbonates. The Murihiku sequence is of lower Mesozoic age and is mainly of volcanogenic origin. Both units have been altered to a low grade metamorphic facies.

Dun Mountain Ophiolite:

The ophiolite is composed of mafic and ultramafic lavas and intrusives of oceanic ridge origin (Coombes et al., 1976). Pelagic sediments above the lavas are absent and are thought to have been eroded before the mid Permian. It appears that in the latest Carboniferous to earliest Permian the converging oceanic crust and lithosphere failed and subduction continued in the eastern portion, whereas the western portion was obducted.

Caples Terrane:

The Caples Terrane includes several lithostratigraphic groups and consist of mainly unfossiliferous volcanolithic greywacke with minor metabasalt, chert and limestone. The terrane is complexly deformed and weakly metamorphosed and is interpreted as an accretionary prism located oceanward of an arc and forearc basin produced by a west-dipping subduction zone. Fossil evidence suggests that accretion of the terrane occurred mainly during the Permian (Korsch & Wellman, 1988). Allochthonous fusilinid Permian limestones occur within the Caples Terrane (Spörli & Gregory, 1980).

Haast Schist:

The schist is regionally metamorphosed up to amphibolite facies grade and lies between the Caples and Torlesse terranes. The nature of the contact between these terranes and the Haast Schist is not well understood, although the schist probably represents the deeper and more deformed part of the accretionary prism.

Torlesse Terrane:

The Torlesse Terrane is a voluminous, dominantly greywacke and argillite belt with minor basalt, chert, conglomerate and limestone that ranges in age from Permian to Early Cretaceous. It is metamorphosed to low grade facies, complexly deformed and contains zones of tectonic melange. It is generally agreed that the terrane is part of an accretionary prism complex and that the sediments were deposited mainly as turbidites in deep marine, trench and slope environments, although very minor shallow marine and freshwater sediments are present. The source of the sediment is probably from a number of regions: derived from Antarctica and deposited in the oceanic trench parallel to the Gondwana margin; pelagic oceanic sediments and basalt; and reworked Torlesse sediments that were exposed and weathered after accretion to the New Zealand margin. Turbiditic sediments have been identified in the Trinity Peninsula Group of the Antarctic Peninsula (Hyden & Tanner, 1981) and in southern Chile (Ramos 1989).

ANTARCTIC REGION

Late Palaeozoic strata have been described from numerous localities on the East Antarctic craton in mountain ranges and nunataks that protrude from the massive Antarctic ice sheet. These sequences are composed of glacial, periglacial and terrestrial coal-bearing clastic sediments that can be correlated to successions on the surrounding Gondwanan continents. Isolated occurrances of equivalent strata have also been identified in parts of West Antarctica including the Antarctic Peninsula.

EASTERN ANTARCTICA

Prince Charles Mountain Basin / Lambert Graben (131)

The Prince Charles Mountain Basin (Lambert Graben) contains a thick sequence of mainly fluvial Permian to Lower Triassic sediments (Amery Group) that were possibly contiguous with the Son-Mahanadi Basin in India before Gondwanan breakup during the Cretaceous (Mond, 1972; McKelvey & Stephenson, 1990; Webb & Fielding, 1991). The graben was probably initiated in the Late Carboniferous-Early Permian (Late Palaeozoic glacial rocks have been tentatively identified) although only Upper Permian-Triassic sediments outcrop. These sediments are downfaulted in uplifted Precambian metamorphics. The basal strata is composed of alluvial fan conglomerates and sandstones (Radok Conglomerate). Overlying the conglomerates is a thick sequence (about 1400m) of coal-bearing clastics of Late Permian age, which in turn are overlain by non-carbonaceous clastics (Flagstone Bench Formation) of ?Permian-Triassic age. The latter unit contains *Dicroidium* plant remains which are of Early Triassic age.

Transantarctic Mountain Basin (123-127)

The Transantarctic Mountain Basin (Beacon Basin) is an elongate basin that lies between the Precambrian East Antarctic craton and the orogenic West Antarctic margin. The basin contains a thick sequence of generally flat-lying rocks, the Beacon Supergroup, which are composed of shallow marine-non-marine quartzose sediments of Devonian age (Taylor Group), unconformably overlain by sediments and volcanic detritus of Latest Carboniferous-Triassic age (Victoria Group). The sequence is capped by basalts and intruded by dolerites of the Jurassic Ferrar Group (Barrett, 1972, 1991; Elliot, 1975). The basin extends from South Victoria Land to the Ohio Range and was probably contiguous with depositional centres in the Ellsworth Mountains and Pensacola Mountains during part of the basin history.

The Late Carboniferous-Triassic tectonic setting of the basin has been described as both a back-arc basin and a foreland basin (Dalziel & Elliot, 1982; Collinson & Isabell, 1987). Whilst both these terms can be applied, the basin is not a typical back-arc or foreland basin and also resembles an intracratonic basin (Barrett, 1991). During Beacon sedimentation the basin was a lowland region flanked by a Precambrian craton on one side and on the other by mountains which included a magmatic arc. The former lowland underwent uplift during the Cenozoic (associated with rifting in the Ross Sea region) to form a major mountain range, the Transantarctic Mountains. Beacon strata may be present in the subsurface in Ross Sea area. A major deformation event during the Late Permian-Triassic, influenced sedimentation patterns in the Transantarctic Basin (Elliot, 1975; Barrett, 1991).

The Victoria Group represents a terrestrial glacial and glacio-marine sequence that is overlain by a generally regressive, pro-delta, delta plain and alluvial floodplain sequence. Silicic volcanic detritus has been reported in Early Permian sediments in the Ellsworth Mountains, and in mid to Late Permian sediments within the basin.

South Victoria Land Basin (122)

Late Palaeozoic terrestrial glacial sediments are preserved in South Victoria Land, which was the site of a major ice sheet centre that spread southeastwards towards the Ellsworth Mountains. Unconformably overlying the glacial sediments (Metschel Tillite) is a coal measure sequence (Weller Coal Measures) which in turn is overlain by massive non-carbonaceous conglomeratic sandstones of the Feather Conglomerate (Barrett & Khon, 1975). Palaeocurrent directions of the latter unit indicate that this coarse grained unit flowed to the northwest and was deposited in a separate basin from the Transantarctic Mountain Basin. Barrett & Fitzgerald (1985) suggested that a transform fault in the Ross Sea, which was proposed by Grindley (1981), may have been responsible for the creation of the separate basin.

North Victoria Land Basin (121)

To the west of the Ross Sea, in Eastern Antarctica, a sequence of Upper Palaeozoic-Triassic sediments are preserved in the North Victoria Land Basin (Rennick Basin). It is a trough like feature whose location coincides with a present day glacier. The Permian sediments are composed of glacial diamictites that are overlain by fluvial sands and shales of the Takrouna Formation. It has been proposed that the Rennick Basin developed as a graben valley that was further incised during glaciation and subsequently filled with detritus by a northward flowing river system (Collinson & Kemp, 1983; Collinson and others, 1986).

West Dronning Maud Land (130)

Scattered outcrops of thin, flat-lying, carbonaceous Late Palaeozoic sediments have been mapped in West Dronning Maud Land (Hjelle & Winsnes, 1972; Larson and others, 1990). Recent palynological studies in the area have indicated that glacial sediments are present and that the overlying periglacial sediments contain *Tasmanites* sp. and acritarchs, suggesting deposition in low-lying, wet areas influenced by brackish marine waters.

Pensacola Mountains (128)

In the Pensacola Mountains on the margin of East Antartica craton, pebbly mudstones (Gale Mudstone) associated with the Late Palaeozoic Antarctic ice sheet are overlain by carbonaceous fluvio-lacustrine clastics of the Pecora Formation (Williams, 1969). The Pensacola Mountains region has a complex orogenic history; the region was deformed during the Late Permian-Triassic Gondwanide Orogen, which is locally termed the Weddell Orogen (Ford, 1972).

WESTERN ANTARCTICA

Antarctic Peninsula (132)

Deformed turbiditic sediments of the Trinity Bay Peninsula Group and correlative units (Hyden & Tanner, 1981; Smellie, 1981; 1987; Storey and others, 1987) are present in the orogenic Antarctic Peninsula. The age of these sediments is not well constrained but it probably ranges from Late Palaeozoic to Triassic. The Permian tectonic setting of this sequence is equivocal, however most workers favour a fore arc setting, although the position of the coeval magmatic arc is unclear. Recycled Permian palynomorphs are also present (Askin & Elliot, 1982) indicating that a vegetated landmass existed in the region.

Ellsworth Mountains (129)

A thick Palaeozoic sequence of strata, which includes Permian sediments, outcrop in the Ellsworth Mountains. The succession was deformed in a series of asymmetric folds during the Permo-Triassic

Ellsworth Orogeny, which was partly contiguous with the Gondwanide Orogen. The age of the deformation is not well constrained; K-Ar age determinations range from 235-254 Ma (Dalziel & Elliot, 1982; Storey and others, 1987). The Permian sequence consists of a glacially derived unit (Whiteout Conglomerate) overlain by the thick, (over 1500m) regressive clastics of the Polarstar Formation. The Permian sediments are probably a downslope equivalent of the sequence in the Transantarctic Basin (Collinson and Isbell, 1987; Barrett, 1991). The Ellsworth Mountains Block appears to have been rotated about 90° in a counter-clockwise direction during the Mesozoic to its present day position (Dalzeil & Elliot, 1982).

PERI-GONDWANAN MICROCONTINENTS

An assemblage of microcontinents (terranes) was present along the Tethyan margin of Gondwana during the Late Palaeozoic. These microcontinents were fragments of Gondwana and extended from Turkey and Iran in the west, to the Australian and south-east Asian region in the east. They include the Kreios, Central Iran, Lut/Helmand, Qiangtang, Lhasa and Sibumasu blocks. Gondwanan biota, including cool water faunas, and Late Palaeozoic tillites have been reported from various locations within these terranes, indicating that they were situated in marginal areas of Gondwana. Mid to Late Permian, warm-water fusulinid limestones are characteristically developed within the terranes, reflecting a climatic amelioration. The exact palaeoposition and original extent of many of the microcontinents is poorly known, due to post Palaeozoic deformation of the blocks and paucity of palaeomagnetic data.

Numerous studies have indicated that Late Palaeozoic rifting occurred along the Tethyan Gondwanan margin, associated with the formation of the Neo-Tethys ocean (Metcalfe, 1988; Sengör, 1984; 1990; Sengör and others, 1988; Koop & Stonely, 1982; Smith, 1988; Klootwijk, 1979; Archbold and others, 1982; Archbold, 1983; Baud & others, 1989; Robertson & Searle, 1990; Nakazawa & Dickens, 1985; Liu, 1989; Nie and others, 1990; Wolfart & Wittekindt, 1980; Bender, 1983). The Late Palaeozoic-Mesozoic tectonic setting of Neo-Tethys is generally considered to be that of a Red Sea-type rift, although recently (Sengör, 1990) proposed that Neo-Tethys formed as a result of retro-arc (back-arc) basin processes, related to an extensive, discontinous continental margin arc that rimmed the northern margin of Gondwana. The microcontinents drifted towards the northern margin of Palaeo-Tethys during the Late Palaeozoic and Mesozoic, and sutured to western, central and eastern Asia, closing the Palaeo-Tethys ocean to form their current configuration (Metcalfe, 1988). The timing of the rifting of the microcontinents from the margin is conjectural, however it appears that Sibumasu left the northwest Australian margin of Gondwana in the late Early Permian and many of the other fragments probably had rifted from Gondwana and moved northwards by the end of the Permian.

INDIAN REGION

PENINSULA INDIA

The intracratonic Gondwanan basins of peninsula India occur in linear, well-defined rifts within the Precambrian crystalline shield, corresponding to the present day river valleys of the Damodar-Son, Mahanadi and Godavari Rivers. The basins are half-grabens or grabens with the maximum sediment thickness adjacent marginal faults, and are preserved as either isolated depressions or elongate basins (Basu & Shrivastava, 1980; Mitre, 1987). The linear basins overlie pre-existing ancient lineaments within the craton, which were reactivated at various times during the Late Palaeozoic and Mesozoic; deposition was more extensive than is presently preserved. The Gondwana basins radiate out from a prominent lineament, the east-northeast trending Son-Narmada structure, which acted as a locus for sedimentation during the Permian in peninsula India. Normal faulting is dominant within the basins and strike directions generally follow pre-existing Precambrian structural trends; post depositional strike-slip faulting has also been recognised (Mitre, 1987). There is minor folding within the basins and fold axes trend mainly parallel to the bounding linear faults.

Earliest Permian deposition in penisula India began with thin glacial sediments that were deposited in topographic depressions on the emergent Precambrian shield, while further north, glaciomarine sediments accumulated on the southern margin of Tethys. Sedimentation during the Permain was dominanted by fluvial activity, which included deposition of Early and Late Permian coal measures. Fluvial deposition continued until the Late Jurassic, when it was succeeded by fluvial-deltaic and paralic deposition during the Late Jurassic-Early Cretaceous (Casshyap & Tewari, 1979; Chatterjee & Hotton, 1986). Late Mesozoic and earliest Cenozoic basic volcanic activity locally intruded and covered the basins, mainly in the north and west.

Satpura Basin (77)

The Satpura Basin occurs along the Son-Narmada lineament and outcrops as an inlier within the extensive Deccan Traps basalt flows. Measured palaeocurrent direction in the sediments are directed towards the northwest (Casshyap & Qidwai, 1974). The preserved sequence generally dips to the north, but post-depositional volcanic activity has obscured the evidence of earlier tectonic events in the basin.

Wardha-Godavari Valley Basin (78)

The north-northwest trending Wardha-Godavari basin is a well defined broad rift structure, delineated by gravity surveys, that contains several sub-basins (Ramanamurthy & Parathasarathy, 1988). The main sub-basin in the north, the Godavari Sub-basin, appears to be fault-bounded on the eastern margin with the basin sequence generally dipping at a low angle to the northeast; synsedimentary faulting probably occurred in the basin during the Permian. Palaeocurrent directions in the basin trend northwestwards.

Son-Maranadi Valley Basins (79)

The Son-Maranadi Basins consist of a number of intracratonic basins that trend east-west and northwest. In the north, Son Valley Basin overlies the Son-Narmanda lineament, and is fault-bounded to the north. It generally contains finer grained lithofacies, including more coal, than the up-dip contiguous Maranadi Basin (Casshyap & Tewari, 1984). Within the Maranadi Valley Basins the major bounding faults alternate along the northeast and southwest margins of the graben and half-grabens; syndepositional faulting has been well documented (Chowdhury and others, 1975). Palaeocurrent directions follow the regional northwest pattern

Koel-Damodar Valley Basins (80)

The northern Koel-Damodar Basins consist of a 375km east-west orientated belt of *en echelon* half-graben troughs, that occur within surrounding Precambrian crust. The underlying basement is generally inclined to the south, towards east-west trending boundary faults, although several basins are fault bounded to the north. Faulting occurred during Permian and younger sedimentation. These basins contain the highest quality coals in peninsula India reflecting relatively high subsidence rates than contemporaneous basins in the region. Palaeocurrent directions also indicate that centripetal dispersal patterns from the surrounding uplands converged into the basins (Casshyap & Tewari; 1984; Rao, 1987).

Rajmahal Basins (81)

Aligned parallel to a north-south regional graben are a series of downfaulted small basins collectively known as the Rajmahal Basins. Gravity studies suggest that the graben is considerably wider than is indicated by the small preserved basins, and Gondwanan sediments are probably present to the north and south of the remnant basins, underlying the present day Ganges alluvial sediments (Basu & Shrivastava, 1980). Permian palaeocurrent directions flow northwards toward the Tethyan sea. Lower Cretaceous Rajmahal Trap volcanics to the east, associated with Gondwanan breakup (Kent, 1991), cover many of the basins.

Rajastan (76)

Isolated fossiliferous Early Permian glacio-marine (Bap Formation) and post-glacial marine sediments (Badhaura Formation) outcrop in western Rajastan and form an important palaeogeographic link between peninsula India and the well known western Himalayan sequence in the Salt Range in northern Pakistan. Drilling and geophysical studies in Rajastan and Pakistan have indicated that a relatively continuous Permian sequence, including Lower Permian coal measures is present at depth beneath the Indus Basin (Rao and others, 1979; Pareek, 1981; Ahmed and others, 1986).

Bangladesh (82)

Permian sediments are present in Bangladesh overlying a basement high (Rangpur Saddle) and the stable shelf (Bogra Slope) that occurs between the Himalayan Foredeep to the north and the Bengal Foredeep in the south. The sediments, including coal measures (probable equivalents of the Barakar Formation in India) where probably deposited in fluvio-lacustrine environments, that locally developed in grabens and half-grabens in crystalline basement (Hiller, 1988).

Northeastern Indian margin

The northeastern boundary of peninsula India in Gondwanan reconstructions of India, Antarctica and Australia remains undefined; many workers consider the region was occupied by continental fragments (Greater India), that now form part of south-east Asia (Veevers and others, 1975; Powell and others, 1988), or an oceanic gulf (Smith & Hallam, 1970). Critical to the argument is an understanding of the early evolution of the Indian Ocean, in the absence of sea-floor spreading anomalies. Studies in the Assam region have confirmed that Permian sediments occur beneath younger Tertiary sediments, and are also possibly present beneath part of present day Ganges and Brahmaputra deltas (Mitra, 1987).

HIMALAYAN REGION

A discussion of the tectonic evolution of the Himalayan region is beyond the scope of this study, the region represents a complex assemblage of terranes (including ophiolites, continental and arc terranes) derived from the northern margin of Gondwana that accreted to Asia. Post-collisional northward indentation of India resulted in approximately 2000km of crustal shortening associated with thrust imbrication and uplift of the Himalayas and Tibet, as well as local north-south extension (Windley, 1988).

Almost continuous Lower to Upper Palaeozoic epicontinental sedimentation in the apparently shallow Palaeo-Tethys Sea on the northern margin of Gondwana was interupted by Permian extension, and the formation of the neo-Tethyan Sea between palaeo-India and the Cimmerian microcontinents (Sengör and others, 1988; Gaetani & Garzanti, 1991). Two Permian tectonostratigraphic domains are present in the Himalaya Mountains, the Lesser Himalayan and Tethyan or Higher Himalayan belts. The widespread occurrance of diamictites, *Glossopteris* flora and *Euydesma* fauna, provide a correlative link between the two regions (Acharyya and others, 1979; Nakazawa & Dickens, 1985; Kapoor & Singh, 1987; Tripathi & Singh, 1985, 1987).

Lesser Himalaya

The lesser Himalaya belt is bounded to the north by the Main Central Thrust and to the south by the Main Boundary Thrust. It contains weakly metamorphosed Late Proterozoic-Upper Palaeozoic sediments, which have been overridden by thrust nappes of high grade gneiss. Permo-Carboniferous Gondwanan related sediments occur from Nepal in the west to Arunchal Pradesh in the east and include tillites and thin coal seams that have been transported southwards in several thrust slices.

Daling Basin (83, 84)

Mainly Permian sediments of the Daling Basin (Kapoor & Singh, 1987; Srivastava and others, 1987) occur almost continuously from the foot-hills of Darjeeling to Arunchal Pradesh in the east. The sediments are poorly fossiliferous but can be correlated to the peninsula India sequence. The sediments, which are wedged between thrusts are highly deformed, generally dip northwards and exhibit a wide range of lithofacies. The basal unit is glacio-marine diamictite and pebbly mudstones comparable to the Talchir Formation in the south.

Stratigraphically overlying the glacial facies are cool climate, marine fine grained sediments that are locally associated with basaltic to andesitic volcanics of the Abor Volcanics, which are equivalent to the Early to ?mid Permian Panjal Trap volcanics in Kashmir (Bhat and others, 1981). These volcanics are related to rifting associated with the initiation of Neo-Tethys. Thin Lower and Upper Permian coals, deposited in fluvial and fluvio-deltaic environments, are present in the sequence. The coals are of high-volatile bituminous rank in Bhutan (Pareek, 1990) and semianthracite rank in Arunchal Pradesh (Misra and others, 1987).

Other occurrences

Diamictite and shales that are equivalent to the Talchir Formation have been reported from central Nepal (Sakai, 1983; Valdiya 1986). Diamictite and marine faunas have also been recovered from the Kumaun region, however the authenticity of other reported occurrences of Lower Himalayan Gondwanan sediments has been questioned (Kapoor & Singh, 1987)

Higher Himalaya

Extending from Pakistan in the west to Bhutan in the east, and north to the Indus Suture is an essentially continuous Palaeozoic to Early Tertiary sequence of sediments, up to 6km thick, that were deposited on the northern passive margin of the Indian Plate in the Palaeo-Tethys Sea. The sediments have been subsequently thrust southwards towards the Indian foredeep and constitute a para-autochtonous sequence. The Permo-Carboniferous succession is dominated by Tethyan marine sediments, although several important intercalations of Gondwanan related sediments occur within the sequence. The Permian sediments occur in mainly isolated synclinoriums along the Himalaya Mountains and record the initial rifting episode between the Indian Plate and northern microcontinents. The following summaries of the preserved sequences are taken mainly from Kapoor & Singh (1987); Tripathi & Singh (1985, 1987); Nakazawa & Dickens (1985) and references contained therein.

Kashmir Basin (86)

The essentially Early Permian Panjal Group (Kapoor & Singh, 1987; Nakazawa & Dickens, 1985) consists of a basal fossiliferous marine unit, the Agglomerate Slates, which is subdivided into a lower glacio-marine diamictite unit and an upper pyroclastic sequence that was associated with an early rift phase. Volcanism continued into the mid Permian and thick intraplate basaltic units (Panjal Trap) filled the rift valleys in Kashmir and adjacent Ladakh. The volcanism was apparently confined to the upper plate margin of the rift, whereas the opposite lower plate margin was affected by block-faulting and only spasmodic volcanism (Baud and other, 1989). Fluvio-lacustrine and lagoonal environments, containing locally abundant biota, were also present in the basin during the mid-Permian. A Late Permian sequence, the Zewan Formation, was deposited in a widespread transgressive phase, probably in the Djulfian.

Spiti-Zanskar Basin (87)

A similar sequence to that in the Kashmir Basin is present to the west in the Spiti-Zanskar Basin (Srikantai 1981; Ranga Rao and others, 1984; Kapoor & Singh, 1987; Gaetani & Garzanti, 1991). The Early Permian marine strata in the basin appears to be coeval with the post-glacial sea level rise and the opening of Neo-Tethys. The summary stratigraphic column in Figure 4 (6) is not well constrained and a hiatus may be present between the Gechang and Gungri Members of the Kuling Formation.

Spongtang Klippe

The Spongtang Klippe in the Zanskar region in the northwestern Himalayas is a composite nappe that represents an obducted ophiolite sequence that overlies a sedimentary melange. Within the klippe, Permian alkaline lavas that are equivalent to the rift related Panjal Traps, are locally intercalated with

Late Permian limestones. Microstructure studies show that the hot lava flowed into unconsolidated calcareous sediments (Reuber and others, 1987).

Kumaun Basin

The Kumaun Basin in the central part of the Himalayas contains a Late Permian shelfal sequence (Kuling Formation), which is equivalent to strata in the western Higher Himalayas, and also a thin siliceous limestone horizon that contains Early Permian faunas.

Central Nepal (89)

In the Tethyan region of central Nepal there is an Upper Palaeozoic sequence of fossiliferous mainly clastic sediments of the Thinu Chu Formation. The clastic sediments contain both Early and Late Permian faunas and are overlain by an argillaceous coal bearing member that contains thin, poor quality coal seams.

Salt Range-Pakistan (85)

The Salt Range in northern Pakistan lies between the Himalayan fold and thrust belt and the complex north-south Sulaiman Mountain arc in Pakistan. The east-northeast trending Salt Range was thrust southward during the Neogene on an evaporitic Eocambrian-Cambrian decollement surface. The preserved Permian sequence is an important location for both floral and faunal biostratigraphic studies (Truswell 1980; Pakistani-Japanese Research Group, 1985). A fluvial-glacial sequence forms the base of the Permian succession followed by marine and locally carbonaceous paralic and fluvio-lacustrine sediments. Sediment was probably sourced from the Sargodah basement high to the south, which appears to have been partly emergent throughout the Permian. Transgressive phases in the mid-Late Permian deposited a fossiliferous, carbonate-rich sequence in the area. Deposition periodically continued in the region, until the Eocene. (Khan and others, 1986; Gee, 1989).

Karakoram region (88)

The Karakoram region is located in a complex tectonic zone at the western edge of the Himalayas. Studies of the Permian sequence in the area have suggested that the northern part of Karakoram area represents a microcontinent that rifted from the Indian passive margin during the Permian (Desio, 1979; Gaetani and others, 1990). Early Permian sedimentation began with marine to fluvial-deltaic deposition in rift troughs, with fully marine conditions being established in the Early Artinskian. Rifting and marine deposition continued throughout the Permian with rapid subsidence in the latest Permian.

Other Occurrences

The Chamba-Bhadarwah (Ballesh-Chamba) Basin is a small isolated synclinal structure located to the southeast of the Kashmir and Spiti-Zanskar Basins, which contains an equivalent sequence of Permian sediments and volcanics and is probably a remnant of a more extensive basin formed during the Late Palaeozoic. Other reported occurrences of Early and Late Permian Tethyan shelfal sequences have been reported from the Mt Everest region and also in Sikkim and Bhutan. However, no Permian volcanic units appear to be present east of the Spiti-Zanskar region in the Higher Himalaya area.

ARABIAN REGION

During the Palaeozoic, the Arabian region formed part of the northern passive margin of Gondwana that bordering the Palaeo-Tethys ocean. Late Palaeozoic epeirogenic activity, possibly related to the Hercynian orogeny, effected the region resulting in the formation of a series of structural highs and the erosion of older Palaeozoic sediments. Permian extensional movements along the northern margin of Gondwana led to the ?Permian-Triassic separation of microcontinents (eg. Iran blocks) from the Arabian Gondwanan margin and the formation of Neo-Tethys. Sedimentation in the region during the Early Permain was generally dominated by clastic deposition (locally of glacial origin), which was replaced by extensive carbonate dominated deposition in the Late Permain.

Northern Oman (73)

The Oman Mountains in northern Oman consist of a complex ophiolite structure of Late Palaeozoic-Mesozoic age. Periodic passive margin extension on the southern margin of Tethys in Oman, which was probably initiated during the Early Permian, led to the development of the deep-water Permian to Mesozoic Hawasina Basin. The basin was subsequently thrust southwards and obducted to its present location during the Late Cretaceous (Glennie and others, 1974; Lippard and others, 1986;. Blendinger and others, 1990; Robertson & Searle, 1990).

The Permian succession in the area contains autochthonous, para-autochthonous and allochthonous sequences of Early Permian clastics and carbonates and Late Permian shelf, slope and basinal carbonates (including reefs), as well as probable mid-Late Permian mafic volcanics of tholeiitic affinity. There is general agreement that Early Permian, non-volcanic rifting, dominated by block-faulting, was followed by mid-Late Permian rifting and axial zone mafic volcanism contemporaneous with deposition of an extensive carbonate shelf to basinal sequence.

Southern Oman (74)

The South Oman Salt Basin and Eastern Flank Area lie to the north of an east-northeast trending basement high, the Huqf-Dhufar Arch, which probably developed during the widespread Hercynian orogeny (Saint-Marc, 1978; Murris, 1980; Alsharhan & St. C. Kendall, 1986). The basinal sequence that continues northwards into Saudi Arabia comprises a Late Precambrian-Cambrian evaporitic unit, which is unconformably overlain by mainly clastics of Early and Mid Palaeozoic age, which in turn are overlain by the Late Palaeozoic-Triassic Haushi Group.

The latter unit consists of a basal, oil-bearing, glacially derived clastic sequence overlain by post-glacial clastics and minor carbonates of the Early Permian Gharif Formation (Hudson & Sudbury, 1959; de la Grandville, 1982; al-Laboun, 1988; Levell and others, 1988). The overlying Late Permian-Triassic Khuff Formation is composed of basin margin clastics that interfinger with an extensive platform carbonate unit that covers the central and eastern region of the Arabian Plate. The dominantly continental Gharif Formation appears to thin northwards towards north Oman. The formation also contains a number of intraformational unconformities in the thinned succession; Blendinger and others (1990) suggested that the unconformities represent contemporaneous uplift in the region, which was associated with the formation of the Hawasina Basin.

Saudi Arabia (70)

Permo-Carboniferous siliciclastics (Unayzah Formation and equivalents) are widespread throughout the Arabian region to the west of the Precambrian shield (al-Laboun, 1984, 1988), with deposition controlled by major regional structures developed during the Hercynian orogeny. The Ha'il-Jawf-Rutbah-Mosul Arch and Mardin Arch in the north, form regional divides between the wide platform to the east and narrow basinal structures to the west. The Unayzah Formation (previously known as the Wajid Formation) thins progressively north and south of the Central Arabian arch. Salt diapirism associated with a Late Precambrian-Cambrian evaporitic unit occurs in the Arabian Gulf region, and locally effects structures in the area, although not to the same extent as has occurred in the Oman region. Sediment was sourced mainly from the western craton, however, local basement highs within the depositional basin may well have contributed sediment.

The Permo-Carboniferous clastics unconformably overlie Palaeozoic sediments and contain sandstones, siltstones, varicoloured shales, minor thin carbonates, marls and coal beds. The formation appears to range in age from Westphalian to Kungurian, although it is not well constrained biostratigraphically. Depositional environments varied throughout the basin but continental facies were apparently dominant with local incursions of marine conditions. Glacial sediments have also been recorded in the southern part of the region, adjacent to Oman (Besems & Schuurman, 1987). During the Late Permian there was an extensive marine transgression (represented by the Khuff Formation) that established a carbonate platform over the entire region (Saint-Marc, 1978, Murris, 1980).

Yeman (75)

A thin glacio-lacustrine unit, the Akbra Shale, is preserved in northern Yeman (Kruck & Thiele, 1982). To the north of the shale sequence, and extending into southern Saudi Arabia, isolated outcrops of poorly understood sandstones have recently been interpreted as a shoreline facies fed by post-glacial braided streams during the Sakmarian, which continued through to the Late Permian as lateral equivalents of the Khuff Formation (Alsharhan and others, 1991).

Zagros Basin (71)

The Early Permian stratigraphy of the Zagros Basin located to the east of the Main Zagros Thrust, is not well known, although drilling has indicated the presence of ?Artinskian clastics and thin carbonates possibly associated with the incoming Early Permian transgressive phases. The sediments appear to have been sourced from a local basement high (Zagros High) to the east. Late Permian sedimentation consisted of widespread, locally thick shelfal carbonates and evaporites deposited in a range of environments including reefs (Szabo & Kheradpir, 1978; Koop & Stoneley, 1982).

Sanandaj-Sirjan Zone

The Sanandaj-Sirjan Zone is a complex belt that forms the southwest margin of Central Iran and may represent a remnant of Neo-Tethys. The zone is separated from the Zagros Basin to the west by the Main Zagros Thrust, which represents a suture zone between the Arabian platform and Eurasian microcontinents. The Sanandaj-Sirjan Zone consists of metamorphic basement unconformably overlain by Palaeozoic to Tertiary sediments. Permian volcanics, clastics and carbonates are present in the zone and it has been suggested (Koop & Stoneley, 1982; Chevron, 1986; Glennie and others, 1990) that the region could represent a zone of crustal seperation between the Central Iran Block and the Gondwanan supercontinent that separated during the Permian. Sengör, (1990) proposed that the Sanandaj-Sirjan Zone was part of a Late Palaeozoic magmatic arc, 'Podastaksasi arc' that was generated in response to 'southward' subduction of Palaeo-Tethys beneath the leading edge of the Gondwana.

Iraq Region (69)

The Early Permian stratigraphic record from northeastern Iraq is not well known and the area may have been non-depositional. In southern Iraq, sediments equivalent to the Unayzah Formation in Saudi Arabia are present. Mid-Late Permian carbonates of the Chai Zairi Formation occur and are equivalent to the Khuff Formation to the south (Buday, 1980; Alsharhan & St. C. Kendall, 1986). In western

Iraq, varicoloured clastics of possible Permo-Carboniferous age were deposited in the Ga'ara Depression in fluvio-lacustrine to ?paralic environments. However recent palynological determination on the sequence (Al-Ameri, 1990), suggests that the sequence is of Middle Triassic age.

Palmyra Fold Belt-Syria (67)

The Palmyra Fold and Thrust Belt in central Syria represents a Permo-Triassic or possibly older failed rift (aulacogen) developed on the Levantine passive margin, which was later inverted by Late Mesozoic and Cenozoic compression. Following the Hercynian orogeny, a major shelf basin formed in the area and accumulated a thick sequence of clastics and thin carbonates of the Doubayat Group in continental to marine environments (Beydoun, 1987; al-Laboun, 1988; McBride and others, 1990).

Southeast Turkey (68)

Early and Late Permian sediments occur south of the Taurus Thrust in southeast Turkey, on the northern margin of the Gondwana. East and south of the emergent Mardin Arch, a Lower Permian a southward prograding, marginal marine clastic sequence, with thin coal seams (Hazro and Gomaniibrik Formations) were deposited on an Hercynian unconformity surface developed on mid Palaeozoic sediments (Ala & Moss, 1974). Reefal carbonates and thin coals of low rank were later deposited in the region during the Late Permian. Further west, Lower Permian coarse alluvium (probably reflecting fault activity) is overlain by deltaic coals. Permian sediments in southeast Turkey thicken southward towards Syria (Cater & Tunbridge, 1992).

Israel Region (66)

A well dated Permo-Triassic sequence (Negev Group) occurs in Israel (Weissbrod, 1976; Eshet & Cousminer, 1986, Eshet and others, 1988) and can be broadly correlated with sequences in neighbouring Sinai and Jordan regions. Hercynian tectonism and associated uplift and erosion was followed by tectonic subsidence and the formation of the Levantine passive margin on the southern edge of Tethys. The Permian section is composed of locally carbonaceous clastics in the lower part, and predominantly carbonate and fine clastics in the upper part. Continental to shoreline facies in the Early Permian were replaced by paralic to shallow marine facies in the latest Permian. Marine conditions were more widespread in the north of the region, whereas the terrestrial influence was more dominant in the south.

AFRICAN REGION

Permian sediments occur throughout the African continent. Sedimentation patterns were strongly influenced by climatic variations, and changing tectonic settings across the centre of the Gondwanan supercontinent. Regional correlation of many of the African Permian sequences is possible, however some of the sequences, especially in central and northern Africa, are continental, poorly fossiliferous and have been oxidised, making regional correlation imprecise.

The following discussion on Permian sediments is divided into several regional groups: the *Karoo sequences* which range from Late Palaeozoic to Jurassic in age, are located in southern, central and eastern Africa in intracratonic, rift and foreland basins and are exemplified in the Karoo Basin in South Africa; *East African Rift sequences* occur from Somalia to Tanzania, and lie within a major rift structure initiated during the Late Palaeozoic, and contain a Karoo type sequence; *"Continental Intercalaire" sequences* occur in west, central and northern Africa range from the Late Carboniferous to Cretaceous (i.e. between Carboniferous and Cretaceous marine flooding events); *Nubian sequences* are marine, paralic and non-marine sequences located in northeast Africa and range from Palaeozoic to the Tertiary, - they were originally thought to be entirely continental; *Atlasic sequences are* sediments associated with the Atlas Mountains orogenic events in the extreme northwest of the Africa continent. (Lefranc & Guiraud, 1990; Kogbe & Burollet, 1990)

KAROO BASIN (17-20)

The Karoo Basin is a foreland basin formed by thrust-belt loading (Cape Fold Belt), which formed an assymmetric basin. The basin is underlain in the north by the stable Kaapvaal Craton and in the centre of the basin by the Precambrain Namaqua-Natal Metamorphic Belt. It is bounded in the south by the Cape Fold Belt and to the east by a monoclinal downwarp. A north-northeast trending graben (Natal Trough) is located in the extreme east of the basin and the east-west trending Karoo Trough is present in the southern part of the basin. In the south, the Karoo Basin sequence is underlain by the Cape Supergroup, a thick passive-margin clastic wedge of Ordovician-Carboniferous sediments (Tankard and others, 1982).

The basin contains a Latest Carboniferous-Triassic sequence of clastic sediments that where deposited in a range of environments from glacial through to marine, deltaic, paralic, alluvial, lacustrine, playa to desert, and is capped and intruded by Jurassic flood basalts and dolerites. The entire sequence is called the Karoo Supergroup. The Carboniferous-Permian glaciogene unit (Dwyka Formation) is overlain by Early to mid Permian coal-bearing clastics of the Ecca Group, which is in turn overlain by the Late Permian-Triassic Beaufort Group. Tectonic activity in the adjacent Cape Fold Belt and faulting in the

Natal Trough region were major influences on sedimentation patterns within the basin. The sediments thicken considerably southwards towards the Karoo Trough, and at the confluence of the linear Natal and Karoo Troughs, in the southeast of the basin, maximum sediment accumulation is probably over 8000m. The proto-Karoo Basin was probably more extensive than its present area (Visser, 1989)

The northern section of the basin overlying the Kaapvaal Craton represents a shallow platform area, whereas the southern rapidly subsiding part of the basin represents an extensive foredeep. Coal deposition is restricted to the stable northeastern part of the basin where subsidence rates were relatively low, and peat swamps could accumulate (Cadle and others, 1990; Cairncross, 1989; Falcon, 1986; 1989). Correlation of Permian units from the northern to the southern part of the basin is uncertain due to rapid changes in depositional facies across the basin. Palaeocurrent studies (Ryan & Whitfield, 1978, Visser, 1983a; 1987) indicate that during Dwyka and Ecca deposition, sediment was mainly sourced from the northern craton and the southern orogenic region, but during Upper Ecca and Lower Beaufort sedimentation, a thick clastic wedge was derived dominantly from the emerging uplands to the south.

Volcanic fragments and ash have been recovered from Permo-Triassic sequences in several localities in the Karoo Basin (Elliot & Watts, 1974; McLachlan & Jonker, 1990). The source of this material has previously been suggested to be in nearby Patagonia and West Antartica where widespread magmatic activity has been demonstrated, although the size of preserved glass shards appear to indicate a nearby source, possibly south of the Cape Fold Belt.

The Karoo Basin differs from other Permo-Triassic basins along the palaeo-Pacific margin of southern Gondwana in that deformation (Cape Fold Belt) was most intense distal to the margin rather than adjacent to the margin near a magmatic arc), as in southern South America and eastern Australia (Cole and others, 1990. De Witt, (1977) and Lock (1980) proposed a flat-plate subduction model to explain this anomaly, the subduction zone was possibly 1000km south of the present Cape Fold Belt. Lock (1980) proposed that the deformation in the Cape Fold Belt occurred along a zone of detachment between the subducting and Gondwanan plates.

CAPE FOLD BELT.

The east-west trending Cape Fold Belt is located at the southern margin of the Karoo Basin and probably represents a foreland fold and thrust belt (de Wit, 1977; Dalziel & Elliot, 1982; Storey and others, 1987). During the Permian and Triassic the Cape Fold Belt was a zone of intense thrusting and folding; several phases of deformation within the orogen occurred from 230-278 Ma (Söhnge & Hälbich, 1983). Up to 25 percent lateral shortening and high-angle thrusts indicate considerably convergence in the region. Large-scale structures including disharmonic and northward-overturned folds characterise the fold belt (Tankard and others, 1982). Hälbich, (1983) suggested that the fold belt bears resemblance to ensialic Precambrian Pan-African belts and associated platforms. Opening of the Southern Altantic Ocean during the Mesozoic has obscured much of the evidence for the origin of the Cape Fold Belt.

FALKLAND ISLANDS / ISLAS MALVINAS (16)

The Falkland Islands consist of a sequence of Devonian to ?Early Triassic sediments that unconformably overlie a Proterozoic gneiss complex. The sequence has been mildly folded and subsequently intruded by two distinct phases of ?Lower Jurassic dyke swarm intrusions, trending approximately north-south and east-west. The Late Palaeozoic sequence unconformably overlies mid Palaeozoic sediments and consists of a basal glacially derived unit which is apparently conformably overlain by marine clastics which in turn are overlain by ?fluvio-lacustrine and tidal flat Lower Permian sequences. The Late Permian-?Triassic Estrecho de San Carlos Formation is composed of fluvial clastics that conformably overlie the Lower Permian units (Greenway, 1972; Bellosio & Jalfin, 1987;). The overall Palaeozoic sequence and structural relationships are identical to the Cape and Karoo Supergroups in South Africa, and it has been interpreted that during the Palaeozoic, the Falkland Islands were located at the southeast margin of the Karoo Basin (Adie, 1952; Visser, 1987); recent palaeomagnetic studies have supported the interpretation (Mitchell and others, 1986; Taylor & Shaw, 1989).

Palaeomagnetic and geologic studies have indicated that the Falkland Islands are probably a microplate that was displaced and rotated clockwise from its palaeoposition near the Karoo Basin to its present day location, after the final folding episode of the Cape Fold Belt. Studies also indicate that the Falkland Plateau is an amalgamation of terranes, which in part may be underlain by oceanic crust, that is arranged such that blocks within the area could move independently of each other. The translation of the Falklands Islands appears to be a result of strike-slip separation of the Antarctic and African plates during the early formation of the Atlantic Ocean (Mitchell and others, 1986; Taylor & Shaw, 1989).

KAROO SEQUENCES

Karoo sequences in southern Africa

Springbok Flats Basin (22)

To the north of the Karoo Basin is the Springbok Flats Basin, an isolated downwarped basin, which lies within the cratonic Kaapvaal Craton (De Jager, 1986). The Permian section is similar to the succession in the northern Karoo Basin to the south, and palaeocurrent directions suggest that the basin was continuous with the Karoo Basin during the Permian (B. Cairncross, pers comm 1991).

Waterburg Basin (23)

The Waterburg Basin lies within the Limpopo Mobile Belt and was possibly contiguous with the Kalahari Basin to the west during the Permian. There is extensive blockfaulting within the basin. Coal deposition probably occurred from the Early to Late Permian, with the younger seams being deposited in predominantly lacustrine enviroments (De Jager, 1986; Falcon, 1986; Macrae, 1988).

Limpopo Basin (24)

The Limpopo Basin is located in northern South Africa and continues northwards into Botswana and Zimbabwe. The basin fill has a shallow dip to the north in the South African sector and may be fault bounded in the north (Ortlepp, 1986). The Limpopo Basin and Soutpansberg-Pafuri Basin to the south lie within the Limpopo Mobile Belt, but little is known of their structural development (De Jager, 1986). Coal deposition in the Soutpansberg-Pafuri Basin probably continued into the Late Permian (Macrae, 1988).

Other Permian Karoo sequences in southeastern Africa (21)

On the northeastern border of South Africa adjacent to Mozambique and in eastern Swaziland, a narrow north-south rift contains a sequence of Karoo strata, including a reasonably complete Permian succession with coal measures. The rift feature is a post-depositional structure which downfaulted the Permian sediments into Precambrian basement; the sediments generally dip towards the east. Although regional palaeocurrent data are not available, it is reasonable to assume that the sediment may have been sourced from the east, possibly from Antarctica. The rift has been extensively intruded by Jurassic dolerite sills causing vertical displacements and locally increasing coal rank to anthracite (Davies, 1961).

Karoo Sequences in Zaire, Angola & Gabon

Zaire Basin (55)

The Zaire Basin (Congo Basin) is an extensive but poorly known intracratonic sag basin that contains an incomplete sequence of Late Proterozoic to Cenozoic sediments. Permo-Carboniferous glacial sediments and post-glacial Permian fluvio-lacustrine sediments, including coal measures, outcrop on the eastern edge of the the basin (Veatch, 1935; Cahen, 1954; Cahen & Lepersonne, 1981). The glacial sediments appear to have been sourced from an elevated region to the east of the basin and shed westward into the Zaire Basin by vast piedmont glaciers. Late Palaeozoic sediments are less than 800 metres thick.

Angola Basin (37)

Little is known about the Karoo sequences of the intracratonic Angola Basin that outcrop in north-central and northeastern Angola. In the north-central region, the basal Lutôe Series occurs as essentially flat-lying strata consisting of Permo-Carboniferous glacial sediments (Rocha-Campos & Dos Santos, in Hambrey & Harland, 1981) that have been interpreted as fanglomerates (Oesterlen, 1976). The upper part of the Lutôe Series consists of continental clastics. In the northeastern region, *Glossopteris* - bearing shales and probable Late Permian-Triassic clastics (Cassange Series) overlie rocks interpreted as glacial diamictites.

Gabon 'basin' (56)

The Permian Karoo sequence in western Gabon contrasts with other sequences in southern Africa in that it contains evaporites, due to the comparitively lower palaeo-latitude position of the region during the Permian. The sequence, which is preserved in a north-northwestern trending basin, contains a basal Permo-Carboniferous glacial unit overlain by post-glacial fluvial sands and carbonaceous lacustrine sediments, which in turn are overlain by an evaporite unit and Late Permian red beds (Micholet and others, 1970). The overall sequence is similar to that in the Sergipe-Algohas Basin in eastern Brazil and the two basins may have been connected during the Permian.

Karoo sequences in Namibia, Botswana, Zimbabwe and Zambia

Ovambo Basin (34)

Subsurface Permian (Karoo) sediments, less than 500 metres thick are present in the Ovambo Basin (Western Etosha Basin) in Namibia. The sediments are preserved in a broad east-west orientated structural depression that is a sub-basin of the Etosha Basin (Momper, 1982). The depression appears to be fault bounded. Lower Permian glacial and fluvio-deltaic deposits, which were sourced from the north of the basin, occur within deeper parts of the trough (Stavrakis, 1985); Upper Permian sediments, the Omingonde Formation, are preserved outside of the trough.

Otjiwaronga Basin (33)

The Otjiwaronga Basin consists of a complex of smaller sub-basins, which produced rapid variations in facies patterns. The northern margin of the basin is fault bounded and the structural trend within the basin is northeast-southwest, reflecting trends in the underlying Proterozoic basement. Overthrusting of basement rocks over Karoo strata along the southern part of the north bounding fault has been recognised (Stavrakis, 1985). Deeply incised valleys, probably produced by glacial scouring, are present in the centre of the basin.

Huab Basin (35)

The distribution of Permian sediments in the Huab Basin is controlled both by the location of palaeo-valleys and by a series of northerly trending synsedimentary faults that produced horst and graben structures (Stavrakis, 1985). Stratigraphic correlation (Ledendecker & Horsthemke, 1990) of the Permian sequence suggests that the Huab Basin may have formed the western margin of the Paraná Basin of South America during the Gondwanan period.

Kaokoland Basin (36)

Permian sediments occur in northwest Namibia and are confined to narrow valleys and troughs in a region of high relief; little is known of the basin's history (Stavrakis, 1985).

Karasburg Basin (32)

More than 1000 metres of Permo-Carboniferous sediments are preserved in the western part of the Karasburg Basin (Warmbad Basin). Glacial erosion, compaction and isostatic rebound strongly affected the western margin of the basin. North-east trending block faulting, possibly associated with the Cretaceous break-up of Gondwana, has produced horst and graben structures within the basin (Schreuder & Genis, 1975; Visser, 1983a).

Kalahari Basin (25-31)

The Kalahari Basin, which extends from southern Namibia into central Botswana, contains Karoo sequences that are continuous with similar sediments in Zimbabwe and South Africa (Green, 1966). The basin is divided into a series of sub-basins; in the central area (Passarge Sub-basin) Karoo rocks appear to have been deposited in a broad, slowly subsiding basin and formed similar lithofacies, whereas along the margins of the basin sediments vary in thickness and facies. The maximum thickness of Permian sediments is approximately 800 metres. Evidence of marine influence in Permian sediments in the western part of the basin (Ncojane and Nosob Sub-basins), and the presence of fresh-water deposits in the east, reflect the regional palaeoslope from east to west/south-west. Karoo sediments were deposited on an erosional surface with significant topographic relief (Visser, 1983b). Over much of the central and southwestern parts of the basin, which are covered by Mesozoic lavas or sands of the Cenozoic Kalahari Beds, the thickness of Karoo rocks is unknown. There is evidence of a fault bounded, complex graben structure that trends northeast-southwest across Botswana, parallel to the mobile belt basement, and opens to the south (Green and others, 1980; Reimann, 1986; Orpen and others, 1989). The nature and age of the graben is speculative, although pre- and syn-depositional Karoo faulting and variable subsidence rates, have been recognised within the sub-basins (Smith, 1984; Clark and others, 1986).

In the northern belt, grabens and half grabens occur along northeast orientated faults and lineaments active during Karoo and post-Karoo times. Deeper grabens are present in Zimbabwe and Zambia to the north and east. In the southeastern and eastern areas of the basin, the outcropping Karoo succession is thicker due to greater subsidence along a series of ridge and troughs within the Limpopo Mobile Belt basement; the edges of the grabens near stable hinge zones were favourable sites for coal deposition. Further west along the southern margin of the basin, deposition was controlled by proximity to the faulted northern edge of the Kaapvaal Craton. To the north of the Kalahari Basin, but separated from it by a basement high that acted as a sediment source, is a major northeast trending graben probably containing thin (<400m) Karoo sediments (Smith, 1984)

Tuli Basin, Sabi-Lundi Basin (38, 40)

The Tuli Basin (Syncline) and Sabi-Lundi Basin overlie the Limpopo Mobile Belt. The Tuli Basin is a northerly faulted half-graben structure that may have been continuous with the Kalahari Basin during part of the Permian (Smith, 1984). Further east, the Sabi-Lundi Basin consists of a north trending syncline (Sabi Basin) and a west-southwest trending basin (Lundi Basin). These two basins were interconnected during Karoo deposition and Permian coal deposition occurred in a featureless swampland at the confluence of the two drainage systems (Duguid, 1986a,b). Much of the basin is covered by Karoo flood basalts, in contrast to the Mid Zambezi Basin, where erosion has stripped the volcanic cover. Consequently, the eastern margin of the basin is not well known, and Permian sediments may extend as far north as is indicated on the accompanying Permian structure map (Plate 1). Coals in the Tuli Basin are very thin, high in ash and extensively displaced by faulting and dolerite intrusions; the Early Permian coal in the Sabi Basin is semi-anthracitic, reasonably high in ash and also affected by faulting and dolerite intrusions.

Mid-Zambezi Basin (39, 41)

The northeast trending Mid-Zambezi basin straddles the Zimbabwe and Zambia borders and contains a non-marine Permian sequence similar to other southern Africa Karoo sequences. A basal glacial diamictite and varved shale interval was deposited unconformably on an undulating Precambrian basement. These sediments were succeeded by post-glacial clastics that grade upwards into argillaceous Early Permian (economic) coal measures, followed by a sandstone facies that indicates a period of renewed energy deposition, which is capped by a thick succession of Late Permian, lacustrine mudrocks, (Madumabisa Mudstones); black-shales and coals also occur locally at the base of the mudstones (Gair, 1959; Bond, 1967; Reimann, 1986; Duguid, 1986b). A supposed Upper Permian marine fish has been reported from the basin (Bond, 1973), however no subsequent work has proved the presence of marine sequences in the basin.

The basin appears to consist of three sub-basins that are separated by a major basement horst, and are aligned along a zone of pre-existing structural weakness. The northwestern margin is fault bounded by a series of northeast trending en echelon faults; the southeast margin forms a hinged southern flank to the basin, giving rise to an overall asymmetric basin profile. Permian syn-depositional and post-depositional faulting has been recorded in the basin. The internal fault geometry and stratigraphy implies that the basin formed as an extensional half-graben (Ophen and others, 1989).

Lower Zambezi Basin

The Lower Zambezi Basin is located in northwest Mozambique, and straddles parts of the Zimbabwe and Malawi borders. The east-west trending basin is separated from the Mid-Zambezi Basin by a basement horst. It is an asymmetric basin that is clearly fault bounded to the south, however in the northern part of the basin, a series of downstepping synsedimentary faults strike obliquely to the southern east-west trending boundary fault. The basin structure is different from the Mid-Zambezi Basin and it appears to have formed in a transtensional regime (Ophen and others, 1989).

To the east a northwest trending sub-basin of the Lower Zambezi Basin in Mozambique and Malawi is a remnant of an originally larger trough. Syn-depositional faulting produced varying rates of subsidence within the basin and consequently coal measure deposition varies rapidly in both thickness and quality in the region (Neto, 1976; Alfonso, 1984). Permian sediments only outcrop in the Mozambique/Malawi region of the Lower Zambezi Basin where locally thick, economic coal measures (Mozambique - Productive Series) were deposited from the Early and Late Permian (Falcon and others, 1984). The southern extent of Permian rocks is unknown due to Cretaceous cover, and they may not extend as far south as is depicted on the accompanying Permian structural map (Plate 1).

Luangwa Basin (43)

The elongate, northeast trending Luangwa Basin in eastern Zambia has a similar depositional development to the Mid Zambezi Basin to the south. The trough is fault bounded and occurs as a graben or as a series of alternating half-grabens that face in opposite directions; a strike-slip tectonic setting has been suggested (Utting, 1976; Zambia Ministry of Mines, 1983; Reimann, 1986; Ophen and others, 1989). The basin contains shaly coals with high ash contents.

Luano and Lukusashi Basins (42)

The Luano and Lukusashi Basins are fault bounded troughs that appear to have a similar structural and depositional history as the Luangwa Basin to the north. Permian coals occur in the troughs, however they are generally of poor quality (Gair, 1960; Zambia Ministry of Mines, 1983).

Kafue and Chunga Troughs

Chunga Trough is a poorly known northeast trending, shallow trough that extends into the Barotse Basin to the west. The Kafue Trough to the south is also poorly known, although limited drilling confirms that a Permian Karoo sequence similar to that in the Mid-Zambezi Basin is present in the basin. The Kafue Trough trends northeast and is separated from the Mid-Zambezi Basin by a basement ridge; the trough appears to plunge to the southwest, truncating the Barotse Basin (Zambia Ministry of Mines, 1983; Reimann, 1986).

Barotse Basin (44)

The Barotse Basin differs considerably from other Zambian basins, as it is not a rift basin but occurs as bowl-shaped, block-faulted basin with gently dipping flanks. A Permian sequence similar to that in the Mid-Zambezi Basin is present, but it overlie Palaeozoic sediments rather than Precambrian metamorphics (Zambia Ministry of Mines, 1983; Reimann, 1986).

Karoo sequences in Mozambique and Malawi (45-48)

Isolated occurrences of Karoo sediments are present in northern Mozambique near the Lugenda River. These sediments include coal measures, however the relationship of the outcrops is not certain (Afonsa, 1984). Other Mozambique Karoo sequences occur within basins that straddle the surrounding countries, for example the Lower Zambezi and Metangula graben. The presence of Permian sediments in the offshore Mozambique Channel has been suggested, based on the presence of seismic reflectors within a possible rift sequence in the Southern Mozambique Basin (De Buyl & Flores, 1984). The age of these possible sediments is speculative, regional consideration indicate that if the sequence is of Karoo age, it may represent Triassic and younger sediments.

In northern Malawi scattered outcrops of Permian sediments are preserved on pre-Karoo basement. They lie on the Nyasa Rise of Rust (1975), which separates the Zambezian and Tanzanian basin complexes, and generally dip eastwards (Haughton, 1967). They may form part of a larger basin, however recent work (Yemane and others, 1989) suggests that during the Late Permian there was significant topographic relief in the region and therefore the small depocentres may have been cut off from the neighbouring basins.

EAST AFRICAN RIFT SEQUENCES

From Tanzania north to Somalia along the eastern margin of Africa a system of linear, fault-bounded grabens contains a rift sequence of Late Carboniferous-Triassic Karoo strata several thousand metres thick, which is overlain by a post-rift, passive margin Jurassic-Cenozoic sequence. The Karoo rocks occur mainly in the subsurface, and in general the facies and age control of the various formations is not well understood, except in Tanzania. The rift sequence was deposited in the 'Malagasy Trough' (Wopfner, in press), which represents a fundamental fracture within the Gondwanan supercontinent between Africa and Malagasy-India. The conjugate Malagasy basins are discussed in the following section as they formed part of the eastern margin of the 'Malagasy Trough'.

Tanga Basin (52)

The oldest sediments in the Tanga Basin (Lamu Embayment, Mombasa Basin) in southeast Kenya consist of thick Late Carboniferous-Early Permian, feldspathic, carbonaceous grits and sandstones that generally fine upwards (Tara Grits), which are overlain by Late Permian-Early Triassic fine grained clastics (Maji ya Chumvi Beds). The sediments were derived from the basement to the west and are downfaulted against Precambrian basement. Sedimentation was initiated by major extensional faulting associated with early rifting between East Africa and Malagasy (Kamen-Kaye & Barnes, 1979, Mbede, 1987).

Mandera Basin

The Mandera Basin (Mandera Lugh Basin) is located in northeastern Kenya and extends into Ethiopia and Somalia. It contains undated continental clastics, 3000-4000m thick (Mansa Guda Formation), of possible ?Permo-Triassic age. A basement high, the Bur High (Bur Acuba ridge) separates the northeast trending Mandera Basin from the Somalia coastal basin to the east and was probably emergent during Karoo deposition. Southwest of the Mandera Basin is a northwest trending major graben structure (Anza Graben Basin) which contains over 2500m of Karoo sediments at the southern end of the graben (Mbede, 1987).

Somalia Coastal Basin

The Somalia Coastal Basin is bounded to the west by the northeast trending Bur High; to the southeast is the present day Indian Ocean. No pre-Jurassic sediments have been recovered from the basin, although Kamen-Kaye and Barnes (1978) noted that Permo-Triassic palynomorphs were found in shales in a petroleum exploration well. However, this reported occurrence has not yet been formally documented.

Ogaden Basin (65)

The Ogaden Basin is located in southeastern Ethiopia and western Somalia and is part of the regional trough that extends along the east African margin. Two major northwest trending fracture zones dominate the basin framework. The age of the basal clastic sediments in the basin is not known; Assefa (1988) referred to it as being Early or Late Palaeozoic. For this study it has been assumed that the sediments are Karoo equivalents similar to strata in the Mandera Basin to the south.

Permian Karoo strata in Ethiopia

To the west of the Ogaden Basin, in southwest Ethiopia, several outcrops of Upper and Lower Permian fluvial clastics (Kari and Gilo Sandstones respectively) unconformably overlie crystalline basement (Davidson and McGregor, 1976). The transport directions of the sediments was towards the south-west.

Palaeozoic glacial rocks (Edaga Arbi Tillite and Enticho Sandstone) in northern Ethiopia were described by Dow and others (1971). Beyth (1972) proposed that the glacial sediments were deposited in a north-south trending trough. The age of the sediments is uncertain; they are either a product of the Ordovician glaciation in northern Africa or are associated with the widespread Late Carboniferous-Early Permian glaciation of Gondwana (Saxena & Assefa, 1983; Caputo & Crowell, 1985). It is also possible that the tillites may have been deposited during both of the glaciations.

Ruhuhu Basin (49)

Over 2500m of latest Carboniferous to Middle Triassic sediments are preserved in the southwest trending, fault-bounded Ruhuhu Basin in southeast Tanzania. These sediments occur in a series of isolated half-grabens or grabens generally tilted to the south, with vertical throws on the bounding faults exceeding 1000m. Deposition commenced with glacial and periglacial sediments (K1), which are overlain by thick, economic, fluviatile coal measures (K2), which in turn are overlain by arkoses and red beds (K3) that grade upwards to fluvio-lacustrine coal measures (K4). The uppermost Permian beds are composed of lacustrine sediments (K5) that dried up eventually leading to a playa-flood plain environment (K6) (Kreuser & Markwort, 1989; Kreuser and others, 1990).

Synsedimentary movements occurred at the onset of deposition in the latest Carboniferous-earliest Permian, near the Early-Late Permian and Permian-Triassic boundaries. Continued rifting led to the widening of the graben structure and hence, to successive overstepping of younger Karoo deposits and onlap over the underlying basement. The present graben configuration is a result of tectonic movements associated with the Mesozoic-Cenozoic East African Rift System. The north-south trending Nyasa Rift (Lake Nyasa) cut the Permian trough at right angles and elevated the Karoo deposits on the eastern upthrown rift shoulder. The preserved sequence represents relics of the original trough that has been faulted into the basement (Kreuser, 1984a; Kreuser and others, 1988, 1990).

Mhukuru Basin and associated basins (50)

The Mhukuru Basin is an isolated synclinal structure perserved within Precambrian basement. The sequence within the basin can be correlated with units in the Ruhuhu Basin to the north; only the upper coal measures from the latter basin are represented in the Mhukuru Basin (Harkin, 1952). Several other small isolated grabens of Karoo strata occur to the northwest and south of the Ruhuhu Basin, including the Rukwa Basin deposits, and the Songwe-Kiwira and Njuga Basins. The sequences within these isolated grabens can generally be correlated to the Ruhuhu Basin (Kreuser, 1984a; Kreuser and others, 1990).

Luwegu Basin (51)

The Luwegu Basin (Selous Basin), a north-northeast trending graben, is the largest basin in Tanzania. Thick Late Permian deltaic and lacustrine deposits (Hankel, 1987; Wopfner & Kaaya, 1991) have been described from the northern part of the basin, although geophysical evidence suggests that Early Permian deposits may be present in older graben structures beneath the younger sediments. Syndepositional faulting in the Late Permian (Kazanian) resulted in an internal drainage system within the basin; this changed in the latest Permian to easterly drainage into the 'Malagasy Trough'.

In the extreme north of the basin several grabens, including the Mikumi/Nyakatitu Basin and Mvuha Basin, are present, separated from the main Luwegu Basin by Precambrian basement. The sediments preserved in these basins generally range from mid Permian to Triassic in age. They consist of continental sediments, including sabka facies, which are overlain by a deltaic-marine sequence of latest Permian-Triassic age (Kreuser and others, 1988). A similar sequence occurs in the Rufiji Basin to the east. None of these coastal basins contain equivalents of the coal measures in the Ruhuhu Basin.

Further south in northern Mozambique, Karoo sediments occur in the Metangula Graben (probably a continuation of the Luwegu Basin to the north), which can be divided into a series of sub-basins (Verniers and others, 1989). Lower Permian fluvial-limnic sediments equivalent to K1-K6 in the Ruhuhu Basin were deposited on a stable intracratonic area; only the lower part of the K4 coal seams are of economic interest. Initial graben development began in the latest Permian, followed by infilling of the basin by fluvial sediments.

MALAGASY

Malagasy's palaeoposition relative to the East African margin is constrained by geophysical and stratigraphic evidence, which indicates that Malagasy was located adjacent to Tanzania, Kenya and Somali (McElhinny & Embleton, 1976, Coffin & Rabinowitz, 1987, 1988). The timing of onset of crustal extension and thinning is not well constrained but extension probably began in the Permian, with sea-floor spreading commencing in the Middle Jurassic.

Morondava Basin (55)

The Morondava Basin is the largest of the three basins in Malagasy, borders the Mozambique Channel and contains Early Permian (Sakoa Group) continental sediments that include glacial and coal bearing facies, and thin marine sediments. These sediments are preserved in the southeast of the basin and unconformably overlie faulted Precambrian basement. The major bounding faults trend north-northwest or north-northeast and were active during Sakoa deposition. As a result of the syn-sedimentary fault activity, thickness and facies vary from subbasin to subbasin; the succession is approximately 2000m thick in the south, but gradually thins to the north of the basin where no Sakoa sediments are preserved (Besaire, 1972; Radelli, 1975; Boast & Nairn, 1982).

The upper part of the Sakoa Group was strongly eroded, probably as a result of fault activity, prior to deposition of the Upper Permian-Triassic Sakamena Group. The Sakamena Group rests with a 12° unconformity on either basement or the Sakoa Group and is more widely distributed than the latter. The Sakamena Group thins from south to the north (4000m to 20m) and is dominantly continental although paralic and marine intervals are present in the section. The basin possibly had restricted circulation and was periodically connected to the northern Tethyan ocean.

Majunga Basin (54)

The Majunga Basin is faulted against Precambrian basement on its eastern margin by the Ambondromary Fault, a probable growth fault, and has a major basement high on its western margin (Boast & Nairn, 1982). Sakamena Group sediments up to 300m thick are preserved in small faulted troughs in the northern part of the basin and may exist, on geophysical evidence, in the deeper central part of the basin

Diego Basin

Middle Permian marine sediments are found in three small subbasins within the Diego Basin in northern Malagasy (Besaire, 1972; Boast & Nairn, 1982). Tectonic breccia overlies basement and forms the base of the Permian section, and is in turn overlain by fossiliferous clastics. Vertical movements in the Late Permian are recorded as a discordance between Permian and Early Triassic strata (Coffin & Rabinowitz, 1988).

NUBIAN SEQUENCES - NORTHEAST AFRICA

Murzuq Basin (61)

The Murzuq Basin (Murzuk Basin) is an intracratonic, saucershape basin bounded to the southwest and southeast by the Hogger and Tibesti cratons respectively, and to the northwest and northeast by basement arches that were uplifted during the Caledonian or Hercynian orogenies (Goudarzi, 1980).

The post-Carboniferous marine sequence is not well understood as most of the sediments are unfossiliferous red beds. Klitzsch (1972) argued that a Permian sequence is probably present within the basin, and informally named the section as the Unar Formation and equivalents. The sequence is sandstone dominant and of fluvial and fluvio-lacustrine origin with the sediment sourced from the south. The sequence may range from the Early to Late Permian in age.

Kufra Basin (64)

The continental Kufra Basin (Al Kufrah Basin) occurs in the common border region of Libya, Chad, Sudan and Egypt (Klitzsch, 1986, 1987; Klitzsch & Wycisk, 1987; Klitzsch & Squyres, 1990). Uplift of northeastern Africa due to the Hercynian orogeny resulted in the formation of an east-west trending structural high over most of Egypt and eastern Libya (Schandelmeier and others, 1987; Schandelmeier, 1988). Marine deposition was restricted to the north of Egypt and an extensive shallow basin, the Kufra Basin, formed in the south. Initial deposition was apparently a result of local glaciation on an area of high relief to the north of the basin. Glaciofluvial and glaciolacustrine sedimentation was followed by the deposition of multicoloured, immature continental clastics with numerous palaeosol horizons. Deposition of such sediments continued until the Early Jurassic.

Tehenu Basin

Early Permian sediments up to about 300m thick have been recorded from the subsurface in northeast Libya (El-Arnauti & Shelmani, 1985; Brugman & others, 1985). The Permian succession overlies shallow marine to paralic latest Carboniferous sediments and contains multicoloured clastics with thin beds of lignite that were deposited in continental environments. Recent studies (Keeley, 1989) indicate that the sediments were deposited in a north-south trending basin, the Tehenu Basin, which was formed as a result of mild crustal deformation in north-east Africa related to the Hercynian orogeny.

Permian sediments in Egypt

The Gulf of Suez appears to have developed as a structural embayment during the Palaeozoic. Carboniferous marine sediments are conformably overlain by poorly dated, Permian sand dominated sequences (upper part of the Ataqa/Quseib Formations) which occur as isolated outcrops and in the subsurface (Said, 1962; Soliman & El Fetouh, 1970; Keeley, 1989). The Permian sediments, which are probably Early Permian in age, appear to be similar to sediments deposited in northeast Libya and in the Sinai region to the east.

CONTINENTAL INTERCALAIRE SEQUENCES - NORTHWEST AND WESTERN AFRICA

Jeffra Basin (63)

The Jeffra Basin (Jifarah Basin), located in southeastern Tunisia and western Libya, contains an almost complete Permian marine sequence that was deposited in a marginal trough on the southern margin of western Tethys (Busson & Burollet, 1973; Bishop, 1975). The basin is bounded to the west, south and east by major basement highs that were reactived and uplifted during the Late Palaeozoic Hercynian orogeny. Post-Hercynian erosion has stripped much of the Palaeozoic succession from these basement highs and formed a major unconformity surface in the region. Subsidence accompanied by local block faulting occurred during the Permian in a zone corresponding to the southern hinge line of the Tethys (Catalano, and others, 1989).

Marine transgressions from the north inundated the basin at various times during the Permian. The Early Permian sediments are relatively thin and composed of clastics and carbonates, whereas the mid Permian interval is thicker (up to 1000m) and consists of dolomites, limestones and anhydritic shales; both units thin southwards, associated with an increase of clastic detrital facies. The Late Permian Tegaba Group overlaps the older Permian units and is composed mainly of fossiliferous carbonates deposited in intertidal to open marine environments, and includes reef facies; equivalent detrital sediments composed of brown and reddish clastics with lignite debris were deposited further landward. Permian successions locally contain hydrocarbon occurrences. The Late Permian sediments thicken northwards to over 4000m along the northern margin of the basin probably as a result of basement downfaulting. An unconformity surface is present at the top of the Permian in many areas within the basin (Lefranc & Guiraud, 1990)

Illizi Basin (62)

The Illizi Basin (Polignac Basin) is part of the Oued Mya Basin (Erg Oriental Basin) and occurs mainly in eastern Algeria to the south of a basement high that separates it from the Jeffra Basin. The southern margin of the basin is bounded by the Precambrian Hogger Craton and its eastern margin is defined by a basement high separating it from the Murzuq Basin in neighbouring Libya. The main Permian unit is the relatively thin Stephanian-Autunian Tiguentourine Formation. The basal part of this unit is composed of multicoloured gypsiferous and dolomitic clays and fine sands of lacustine origin containing stromatolites and fish fauna; the upper part contains fine grained sands and clays and minor plant material of continental origin. The sequence is separated by an important erosional hiatus from the overlying continental red beds of ?Permian-Triassic age. Both units are poorly constrained biostratigraphically (Fabre, 1970; Bertand-Sarfati & Fabre, 1972; Lefranc & Guiraud, 1990). The basin may have been continuous with the Jeffra Basin during part of the Permian

Becher-Abadla Basin (60)

The Becher-Abadla basin is located in northwestern Algeria, close to the northern edge of the Sahara Craton, on the western margin of the Oued Mya Basin. The Permian succession is very similar to that of the Illizi Basin to the east, and occurs within the Série d'Adadla, a Stephanian-Autunian sequence over 1500m thick. The lower member consists of gypsiferous shales with intercalated sandstones and limestones and contains floral and faunal remains. The upper member is a non-fossiliferous red bed unit. The formation appears to be conformable throughout and dips at about 10° to the west (Fabre, 1970; Bertand-Sarfati & Fabre, 1972; Morel and others, 1981; Doubinger & Fabre, 1983). Sediment was sourced from the west, probably from the active Hercynian Moroccan region, and was probably more extensive than is indicated on the accompanying map (Plate 1), extending southeastward towards the Saoura Trough. The basin is in a foreland position relative to the active Hercynian Orogen in Morocco. An increase in subsidence rates in the basin from the Lower Carboniferous to the Late Carboniferous-Permian is probably related to activity in the orogen (Fabre, 1985).

Taoudenni Basin

Poorly known post-Carboniferous red bed sediments occur around the periphery of the Taoudenni Basin in central Western Africa, and have been identified in seismic profiles in the centre of the basin. These sediments overlie Late Carboniferous lake deposits and part of the sequence may well be of Permian age, based on regional considerations (Fabre, 1970; Lefranc & Guiraud, 1990).

Tesoffi Graben

To the east of the Taoudenni Basin in northeast Mali there is a sequence of coarse grained, reddish detrital sediments, the Tezzofi Formation, that have been assigned a Late Permian-Triassic age. The sediments appear to have been partly sourced from nearby Permian alkalai intrusives and occur within a north-south graben. The graben is located on the eastern margin of the West African craton, which coincides with the major Pan-African suture zone. Reactivation of this suture, which marks the collisional boundary between the Precambrian west and central cratonic regions of Africa, appears to have occured during the Permian and formed the Tesoffi Graben rift. Late Permian folding in the Saoura Trough to the southeast of the Becher-Abadla Basin, also appears to be associated with Permian reactivation of the suture (Liegeois and others, 1983; Lefranc & Guiraud, 1990).

Illumeden Basin (59)

A sequence of Early to Late Permian continental sediments (Izegouandane Series) were deposited in the Illumeden Basin, which is located in Niger to the south of the Precambrian Air Massif. The sequence consists of an apparently conformable Permian section that is separated from Late Carboniferous and Triassic sediments by an unconformity. The Izegouandane Series contains several formations consisting mainly of reddish sandstones and interbedded clays with minor marls and conglomerates that were probably sourced from an area to the south of the basin. The sediments were deposited in fluvial, fluvio-lacustrine and possibly aeolian environments, and contain locally abundant silicified wood. The upper part of the unit contains detrital analcite of igneous origin; contemporaneous fault activity also occurred in the region (Bigotte & Obellianne, 1968; Fabre, 1985; Lefranc & Guiraud, 1990).

Ghana Basin (58)

A sequence of predominantly fluvio-lacustrine, multicoloured unfossiliferous clastic sediments (Efia Nkwanta Series) occurs in grabens along the coastal region of Ghana, and unconformably overlies the Lower Carboniferous Takoradi Shale (Crow, 1952; Bär & Riegel, 1974, 1980). Stratigraphic correlation of the probable Permian and older Palaeozoic sequences in Ghana have indicated that they are remnants of the Maranhao (Parnaiba) Basin, an extensive Gondwanan basin now confined to Brazil. Current directions in the Permian sequence indicate a sediment source from the northeast, consistent with the palaeoposition on the northeast margin of the Maranhao Basin.

Igneous activity in northern Africa

Late Carboniferous and Permian alkaline granite, syenite and carbonatite complexes have been reported from several localities in northern Africa (Liegeois and others, 1983; Black and others, 1985; Curtis & Lenz, 1985; Schandelmeier, 1988; Vail, 1989). The complexes are located in zones of weakness within the crust; magmatism appears to be triggered by changes in stress patterns within the crust, for instance, shearing due to changes in plate motions.

ATLASIC SEQUENCES

Moroccan Intermontain Basins.

Early Permian (Autunian) continental sediments and volcanics are present in a series of isolated intermontane grabens within the Hercynian basement in central Morocco (Van Houten, 1976, El Wartiti, 1990a). Recent dating suggests that sedimentation may have continued into the Late Permian (El Wartiti, 1990b) in several basins. Volcanism began at the same time as sedimentation and continued throughout the Permian; tuffs, lavas and intrusions of generally calc-alkaline composition occur within the grabens. The volcanism was associated with a late Hercynian compressional regime, which activated a dense network of fractures within the basement, often producing transcurrent faults. The structure, sedimentology and biota of central Morocco strongly suggest that the region was a block linked to both Western Europe and North America during the Permian.

SOUTH AMERICAN REGION

Permian sediments occur in South America in various tectonic settings ranging from extensive intracratonic basins located on crystalline basement, to marginal basins associated with the western and southern orogenic margin of the continent (Samfrau Orogen). Locally abundant volcanic and plutonic rocks also occur in the orogen. The proto-Andean orogenic margin can be further subdivided into the northern, central and southern areas.

INTRACRATONIC BASINS

Parnaiba Basin (15)

The Parnaiba Basin (Maranhao or Piauí-Maranhão Basin) is a dish-shaped intracratonic basin located in northeast Brazil, which contains a relatively continuous Mid Palaeozoic to Mid Triassic sequence. From the Late Carboniferous onwards continental deposition dominated the basin. The Permian section is composed of the basal Pedro do Fogo Formation, which consists of siltstones and intercalated sandstones, with numerous chert concretions, hiatuses and local disconformities overlain by reddish sandstones with minor carbonate and evaporites of the latest Permian Motuca Formation. Lacustrine environments dominated the basin during the Permian, although fluvial, aeolian and playa deposition did occur in a climate that oscillated from generally semi-arid to warm subhumid and arid. The Parnaiba Basin was connected to the Amazon Basin during part of the Palaeozoic, however Permian deposition occurred in an internal drainage basin with slow subsidence in an overall stable tectonic setting (Mabesoone, 1977; Schobbenhaus, 1984).

Amazon Basin (14)

The Amazon Basin is an elongate Palaeozoic intracratonic basin that trends east-west across central Brazil. The basin contains two major subbasins, the Upper (Solimões Basin) and Middle-Lower Amazon Basins. The Upper and Middle Amazon Basins are separated by a north-south trending basement high, the Purus Arch, which was active during the Late Palaeozoic. The Palaeozoic sequence within the basin is similar to that of the Parnaiba Basin to the west, except the Amazon Basin contains a thick (over 1200m) latest Carboniferous-mid Permian evaporite sequence, the Nova Olinda Formation. Renewed rifting during the mid Carboniferous resulted in continuous subsidence in the subbasins with the thickest Permo-Carboniferous accumulation occurring in the eastern part of the basin.

The evaporite sequence overlies Late Carboniferous fusulinid shallow marine carbonates and sandstones and is overlain by a Late Permian semi-arid to arid continental sequence. The evaporitic Nova Olinda Formation was deposited in an overall regressive regime in a range of environments subject to marine and continental influences, from open marine and lagoonal environments, including local deltas, to fluvial, lacustrine and playa environments. Marine waters entered from the west and deposited a cyclic sequence of carbonates and evaporites, which include anhydrite, halite and sylvinite. The Purus Arch was a platform subject to intense evaporisation and at times formed a temporary barrier to the open sea to the west. Uplift of the Hercynian proto-Andean Mountains to the west (and possibly lower sea level) isolated the basin from marine influences and continental conditions prevailed during deposition of the uppermost part of the Nova Olinda Formation and overlying Andira Formation (Szatmari and others, 1974, Sad and others, 1982; Mosmann and others, 1984).

Sergipe-Alagohas Basin (57)

The Sergipe-Alagohas Basin is a small Latest Palaeozoic-Mesozoic complex graben structure located on the coastal margin of northeast Brazil. The basin contains a basal diamictite and conglomeratic sequence (Batinga Formation), overlain by a clastic fluvio-lacustrine sequence containing interbedded carbonate and chert of probable Early to Late Permian age (de Lima & Sundaram, 1982; Schobbenhaus, 1984; Rocha-Campos & Archangelsky, 1985). The basin may have been continuous with the 'Gabon Basin' in western Africa that was located to the southeast of the basin during the Permian.

Paraná Basin (12-13)

The Paraná Basin, which is located mainly in southern Brazil and extends into parts of Uruguay, Paraguay and Argentina, contains a discontinuous mid Palaeozoic to Mesozoic sequence over 5000m thick. The intracratonic basin has a history of several subsidence phases that led to the deposition of a series of depositional sequences separated by major unconformity surfaces. Subsidence periods during the Silurian, Devonian and Permo-Carboniferous are referred to as a continental interior fracture phase and those in the Permo-Triassic and early Mesozoic as an interior sag basin phase; the latter phase was associated with extensive flood basalts, similar to other Gondwana continents (Zalán and others, 1987). Intraplate stresses associated with the proto-Andean orogeny, glaciation and sea level variations were the dominant influences on Permian sedimentation.

The structural framework of the basin consists of a pattern of criss-crossing lineaments that probably represent long-lived tectonic elements inherited from the underlying heterogeneous Precambrian basement. The dominant lineament orientations in the southern part of the basin are northwest and northeast. These zones are 20-100 km wide and extend over 500 km in length. Two of the northwest trending lineaments are extensions of offshore fracture zones and have strongly influenced sedimentation and facies distribution in the basin (Fulfaro & Landim, 1976; Zalan and others, 1987; França & Potter, 1991).

The Permian sequence is represented by a basal Permo-Carboniferous glacial unit, the Itararé Group (over 1200m thick), that was deposited mainly in the northern part of the basin i.e. to the north and west of the Ponta Grossa Arch. Following Itararé Group sedimentation the depocentre moved southward, associated with an apparent uplift of the eastern and western margins of the basin, resulting in the deposition of the post-glacial Guatá Group. The Guatá Group consists of a coal-bearing unit (Rio Bonito Formation) and an overlying marine to marginal marine unit (Tatui Formation) in the north, and the equivalent Palermo Formation in the southern part of the basin. Conformably overlying the Guatá Group is a relatively thin but important marker horizon in the the basin, the Irati Formation, which is the basal unit of the Passa Dois Group and appears to have been deposited during a period of basin stability. An overall regressive sequence, represented by the marginal marine Serra Alta, Terezina and Corumbatai Formations and the continental Rio Rasta Formation characterises the Late Permian sedimentation of the Passa Dois Group (Bigarella and others, 1967; Schneider and others, 1974; Fulfaro & Landim, 1976). Equivalent units have been recognised in Uraguay in the southeast margin of the basin (Mones & Figueiras, 1980).

Other Permian occurrences in Brazil

South of the Amazon Basin, isolated possible remnants of the basin occur in the poorly known Alto Tapajós Basin, which contains a thin sequence of reddish calcareous clastics overlying a poorly dated ?Lower Carboniferous sequence. To the west of the Sergipe-Alagohas Basin isolated occurrences of calcareous sediments containing *Lueckisporites,* (Santa Brígida Formation) that occur within the mainly Mesozoic Jatobá and Recôncavo Basins (de Lima & Sundaram, 1982; Rocha-Campos & Archangelsky, 1985).

Chaco-Paraná Basin (11)

The Chaco-Paraná Basin in Argentina is a continuation of the Paraná Basin to the northwest, and consists of two major sub-basins separated by a northeast trending basement high. The basin was probably partially contiguous with the Paraná Basin to the northeast and was possibly connected to the Sierras Australes Basin to the southeast. Permian rocks occur in the subsurface and appear to contain a sequence that is dominantly terrestrial, in contrast to the Paraná Basin. A thick Permian basal diamictite, the Ordonez Formation (Russo and others, 1980; Russo & Archangeklsky, 1987), equivalent to the Sachavoj Formation of Padula and Mingramm (1969a), is overlain by the mid to Late Permian continental Victoriano Rodriguez Formation.

Ventania or Sierras Australes Basin

The tectonic setting of the Sierras Australes Basin (Ventania Basin) is not well understood. Ramos (1984) proposed that it developed on the plate margin between northeast Gondwana and a southwest

Patagonian microplate, whereas Harrington (1970), proposed that the basin represents an aulacogen. However, most workers suggest that the basin was a backarc basin behind a Late Palaeozoic and earliest Mesozoic magmatic arc during the Permian (Forsythe, 1982; Uliana and Biddle, 1987; von Gosen and others, 1990). The Permian Pillahiunco Group, lies unconformably on Ordovician to Devonian shallow marine clastics, and contains a basal diamictite unit (up to 2000m thick), which was probably sourced from the west and southwest, as indicated from palaeocurrent data (Rocha-Campos & Archangelsky, 1985). Conformably overlying the diamictites is an Early Permian fossiliferous shelf sequence overlain by a littoral to non-marine unit the Tunas Formation. The age of the latter unit is not well known but it appears to range into the early Late Permian. Following, and possibly during deposition of the Tunas Formation, crustal shortening occurred in the region and a complex northwest trending fold and thrust belt developed in a narrow zone on the southwest margin of the basin.

Colorado Basin (8)

A similar sequence to the Ventania Basin has been intersected by drilling in the offshore Colorado Basin (Uliana & Biddle, 1987, Andreis and others, 1987a). The sequence occurs within a down-faulted blocks in the deeper section of the east-west trending basin, and is unconformably overlain by younger sediments.

VENTANIA / SIERRAS AUSTRALES FOLD BELT

The Precambrian basement and Palaeozoic cover sequence on the southern margin of the Ventania Basin were effected by a crustal shortening event during the Late Permian to Early Triassic (Gondwanide Orogen) that formed a sinuous, generally northwest trending, eastern fold belt and western fold and thrust belt (Sierras Australes Fold Belt). The initial folding and shearing event affected the cover sequence and produced folds that verge northeastwards towards the basin. Continuing rotational deformation resulted in imbrication of the basement rocks to the southwest and associated folding, shearing, metamorphism and thrusting in the region. The final deformation event was strike-slip shearing on subvertical shear planes in an overall sinistral transpressive regime (von Gosen and others, 1990). The western and northwestern extension of the fold belt is uncertain and there is no evidence for a connection to the orogenic Andean Precordillera on the western margin of the continent.

NORTHERN ANDEAN OROGENIC REGION

The northern Andean orogenic region refers to the region including Ecuador, Columbia and western Venezuela. Venezuela, Ecuador, and Columbia are composed of a mosiac of terranes (containing both continental and oceanic crust) that accreted to the continental shield (Guiana Shield) at various times from the ?late Palaeozoic to Cenozoic. Permian igneous, metamorphic and orogenic activity has been recorded in Columbia (Mégard, 1987; Restrepo & Toussaint, 1989) and in Venezulea (Shagam, 1975; González de Juana and others, 1980). The Late Paleozoic evolution of the Venezuelan region is uncertain due to its tectonic setting between the Andean belt and the complex Carribean region.

Mucuchachi Basin (2)

A thick Late Palaeozoic sequence occurs in the Mucuchachi Basin, which is located in the northeast trending Merida Andes in western Venezuela. The basin was an actively subsiding trough during the Late Palaeozoic that was subsequently deformed at the end of the Permian, an event that is probably associated with the emplacement of granite plutons in the region. The Permo-Carboniferous sequence can be assigned to three main units, the Mucuchachi, Sabaneta and Palmarito Formations that unconformably overlie Early Palaeozoic or Precambrian rocks. The former unit is a thick (over 5000m) turbiditic sequence that was deposited in the axis of the trough. The age range of the unit is uncertain but it was probably deposited during the Middle Carboniferous to earliest Permian. The Sabaneta Formation is a thick molassic, reddish, predominantly fluvial succession, deposited as a facies equivalent to the Mucuchachi Formation and possibly the lowermost Palmarito Formation. The latest Carboniferous to Permian Palmarito Formation was mainly deposited under marine conditions and is one of the most widespread stratigraphic units in northern South America. A series of marine trangressive-regressive cycles has been recognised in the Late Palaeozoic sequence. Deposition ceased in the basin near the end of the Late Permian in response to orogenic movements associated with the Tardihercynian orogeny, an event that is recognised in both the northern and central Andean regions (Arnold, 1966; Shagam, 1975; González de Juana and others, 1980; Mégard, 1987; Rocha Campos & Archangelsky, 1985; Sanchez, 1984).

Perija Trough (1)

The Perija Trough is located in the Perija Sierra in western Venezuela. Permian sedimentation was initiated in the Early Permian with deposition of the marine Palmarito Formation, which unconformably overlies Carboniferous deposits. The Palmarito Formation ranges from the Early to Late Permian in age (Leonardian to Guadalupian) and is composed of basal fine grained clastics and an upper carbonate member. Fresh water marls and shales overlie the marine carbonates, which in turn are overlain by dacitic to rhyolitic volcanics of the La Gé Group (Shagam, 1975). Upper Paleozoic deposits are overlain discordantly by Mesozoic-Cenozoic sediments; the break in sedimentation is a reflection of of the widespread effects of the Late Permian orogenic activity in the region (Shagam, 1975; González de Juana and others, 1980; Restrepo & Toussaint, 1989; Sanchez, 1984).

Permian sediments in Colombia (3)

Early Permian marine, dominantly carbonate rocks that were deposited on Carboniferous sediments in a basinal area in Columbia are probabaly equivalent to the Palmarito Formation to the north. The entire Palaeozoic sequence, including Devonian sediments, was folded during a Late Permian tectonic event comparable to the Late Hercynian orogenic movements recognised in the central Andes. Poorly dated red beds and clastics of the Cuche Formation are possibly partly Permian in age although their relationship with the Palmarito Formation equivalent is unknown (Mégard, 1987; Rocha Campos & Archangelsky, 1985; Mojica & Dorado, 1987)

CENTRAL ANDEAN OROGENIC REGION

The central Andean orogenic region refers to the Peruvian, Bolivian and the northern Chilean region and represents a complex and poorly understood tectonic regime. Several models have been proposed for the evolution of the Central Andean region, although most workers agree that Late Palaeozoic deposition in the area was probably not related to oceanic subduction (Dalmayrac and others, 1980; Pitcher and others, 1985; Mégard, 1987; Breitkreuz and others, 1988, 1989; Sempere, 1989; Rocha Campos & Archangelsky, 1985). Early Permian marine carbonate deposition occurred in an intracratonic trough, overlying thinned continental crust between the cratonic Brazilian Shield to the east and the Precambrian Arequipa Massif to the west, which probably extended offshore of the present day coastline. A major deformation event at about the Devonian-Carboniferous boundary (an early phase of the Hercynian Orogeny) was followed by continental to marine deposition during the Carboniferous and Early Permian. A relatively mild mid-Permian orogeny, the Tardihercynian Orogeny, was followed by deposition of red beds and the emplacement of Late Permian-Triassic volcanics and intrusives. The origin of the orogenic movements is enigmatic and may be related to stresses generated to the west of the Arequipa Massif and transmitted through the Precambrian block.

Tarija-Titicaca Basin and Mitu Rift (4, 5)

The Tarija-Titicaca Basin refers to a basinal region in Bolivia and northern Argentina that is probably an extension of the Peruvian Palaeozoic trough to the north. The elongate trough has been referred to as a back-arc basin (Sempere, 1989), however the location of the magmatic arc in the region during the Permian is not well established; it has also been referred to as a foreland basin (Ramos, 1990). The Mitu Rift refers to the area containing volcanics and intrusives of the Mitu Group. Permian deposition was initiated after minor disruption in sedimention at the end of the Carboniferous. A thick succession of Early Permian (Wolfcampian to Leonardian) shelf carbonates, interspersed with black shales and sandstones accumulated. In some areas, the dominantly carbonate unit gives way to paralic sandstones and thin coal measures or reddish, aeolian and fluvial clastics; intercalated tuffs are also present in the southern area. Carbonate deposition was probably continuous with the Amazon Basin to the northeast. The whole section was folded and locally block faulted during a mid Permian, late Hercynian deformation event. After a period of erosion reddish continental clastics and volcanoclastic molasse and volcanic rocks of the Mitu Group were deposited. Extensional faulting continued from the Late Permian to the Early Triassic in what appears to be a continental rift rather than a back arc environment. Volcanic rocks range from andesitic to peralkaline, and the intrusives are crustally-derived sub-alkaline granodiorites and monzogranites (Newell and others, 1953; Helwig, 1972, Pitcher and others, 1985)

Northern Chile (6)

A shallow marine carbonate platform containing terrestrial felsic and mafic volcanics dominated northern Chile during the Early Permian. Limnic and brackish sedimentation also occurred in the platform succession, which indicates that a chain of volcanic islands emerged from the shallow central Andean sea. The Late Permian stratigraphic record in the area was dominated by terrestrial sedimentation and volcanism (Bahlburg and others, 1987; Breitkreuz and others, 1989). Breitkreuz and others (1988) proposed that the region does not represent an active Late Palaeozoic subduction regime as is present in the southern Andes, but rather a region of extensive volcanism in an intracontinental rifting environment. They have suggested that the rifting was due to strike-slip activity related to oceanic plate movement and terrane accretion to the south.

SOUTHERN ANDEAN OROGENIC REGION

The southern orogenic area represents the western margin of South America from approximately 30°S southward to southernmost Patagonia. In southern and central Chile and western Argentina the presence of a Late Palaeozoic eastward dipping subduction complex has been suggested by many authors (Forsythe, 1982; Uliana & Biddle, 1987; Hervé and others, 1987; Hervé, 1988; Ramos 1988b; Ramos and others, 1986). During the Devonian, subduction along the margin shifted westward in response to accretion of the Chilenia terrane and subduction under the proto-Precordillera ceased. Subduction resumed during the Carboniferous, however the subduction zone was located to the west of the previously accreted Chilenia terrane. Subduction of the oceanic plate was accompanied by the formation of a magmatic arc and the accretion of turbidites, forearc basins and minor exotic terranes to the margin, producing widespread metamorphism. A short interruption to sedimentation at about the Permo-Carboniferous boundary was probably been associated with the relatively minor Atacama orogenic movement. The Sanrafaelic orogenic phase in the mid Permian produced intense folding and thrusting, and resulted in the formation of a major angular unconformity surface in the region. The orogenic activity appears to have been associated with eastward migration of the magmatic arc. A change in relative plate motion at the subduction zone has been proposed as a possible cause of the Sanrafaelic orogeny (Ramos, 1988b). Widespread explosive vulcanism and felsic plutonism, with minor continental sedimentation characterises the Upper Permian to Triassic stratigraphy in the region.

The magmatic arc turns westward at about 38°S and trends along northern Patagonia. Ramos (1984) and Mpodozis & Ramos (1990) suggested that this was the result of accretion of a Patagonian microcontinent to southern Gondwana during the Permian, possibly associated with the Ranrafaelic orogeny. They evoked the presence of an active southwesterly-directed subduction zone beneath the Patagonian microcontinent that ceased with the collision of Patagonia and southwest Gondwana. However, the evidence and location of the suture zone representing the former subduction zone has not been recognised. Floral evidence suggests that the Late Palaeozoic climate in Patagonia was temperate to subtropical in contrast to the cold conditions experienced in most of Gondwana (Cuneo, 1989). The Permian tectonic evolution of the northern Patagonian region is also not well understood and further study is required in the Patagonian region in order to establish the boundaries and nature of the possible allocthonous terrane.

Paganzo Basin (10)

Fluvial, playa and aeolian facies of the La Colina Formation and equivalents (up to 800m thick) dominate the Early Permian sequence in the Paganzo Basin. The basin is separated from the Chaco-Paraná Basin to the east by the Pampean Arch, although the basins may have been connected during part of the Palaeozoic. To the west, the basin was bounded by the emerging proto-Precordillera and a Late Palaeozoic magmatic arc. Tectonically, the basin is a foreland basin initiated during the Early Carboniferous, and deformed during the mid Permian; deformation increases in intensity to the west. Minor basaltic flows and sills that occur at the base of the continental La Colina Formation have been dated at 296 ± 6my. The more arid upper part of the La Colina Formation and equivalents, probably extend into the Late Permain. The basin was connected to the predominantly marine, back arc or interarc basins to the west during the Carboniferous and possibly during the Early Permian (Amos, 1981; Rocha Campos & Archangelsky, 1985; Azcuy, 1985; Azcuy and others, 1987b; Limarino & Spalleti, 1986; Ramos and others, 1986; Limarino & Césari, 1988).

Calingasta-Uspallata, Rio Blanco and Puna Basins

The Puna Basin is located to the northeast of the Paganzo Basin and contains an Early Permian, predominantly carbonate unit over 200m thick, the Arizaro Formation. The formation contains minor volcanic intercalations (Breitkreuz and others, 1989) and during the Early Permian deposition was probably continuous with the Copacabana Group to the north. The basin appears to be more closely related to the central Andean region than the southern region. To the south of the Puna Basin, within the Cordillera region, lies the Rio Blanco Basin and its southern extension, the Calingasta-Uspallata

Basin; both basins were probably foreland basins during the Permian (Ramos, 1990). Early Permian marine facies, the Cerro Agua Negra Formation are present in the Rio Blanco Basin, whereas to the south in the Calingasta-Uspallata Basin, Early Permian marine, paralic and continental facies have been identified. As in the Paganzo Basin to the east, the Late Carboniferous to Permian deposition in the region reflected an increase in aridity, as a warmer climate was associated with an overall regressive regime (Amos, 1981; Rocha Campos & Archangelsky, 1985; Azcuy,1985; Lopez Gamundi, 1987).

San Rafael Basin

The San Rafael Basin is a northwest trending basin bounded by basement highs to the north and east, and the North Patagonian Craton to the south. The basin was open to the proto-Pacific ocean to the west. The basin consists of a Late Carboniferous to earliest Permian regressive marine-deltaic-fluvial sequence up to 2000m thick (El Imperial Formation), which is unconformably overlain by an alluvial fan facies. This in turn is unconformably overlain by volcanics, pyroclastics, intrusives and thin intercalated, predominantly semi-arid to arid continental sediments (locally carbonaceous) of the Late Permian Sierra Pintada Group (Azcuy, 1985; Azcuy and others, 1987a). The basin is located within the orogenic margin and was probably a shallow bay in the Late Palaeozoic that was infilled by prograding sediments, to form a continental basin in the Late Permian.

Tepuel-Genoa Basin (9)

The Tepuel-Genoa Basin (Central Patagonian Basin) contains a thick Carboniferous marine sequence overlain by the latest Carboniferous to Early Permian Rio Genoa Formation of the Tepeul Group. This formation is a thick (up to 1200m) siliciclastic wedge of stacked progradational/aggradational deltaic sediments that contain thin coal seams (Andreis and others, 1987b; Andreis & Cuneo, 1989; Uliana & Biddle, 1987). Palaeocurrent data suggest derivation from the northeast, and plant fossils indicate deposition in a moist, temperate to subtropical climate during the earliest Permian, probably reflecting maritime influences. The basin is considered to be a forearc basin (Hervé and others, 1981, 1987; Forsythe, 1982) or a marginal basin due to the lack of volcanic material within the Rio Genoa Formation (Andeis & Cuneo, 1989); erosion may have removed mid to Late Permian sediments from the basin.

La Golondrina Basin

The La Golondrina Basin is an informal name given to poorly known Permian sediments deposited on the Deseado Craton in eastern Patagonia. The La Golondrina Formation is preserved in a series of depressions and consists of arkosic conglomerates, sandstones, minor shales and locally carbonaceous mudstone deposited in alluvial facies, probably during the Early Permian. Poorly known quartz sandstones and conglomerates of the La Juanita Formation are also present in the region, and are possibly of Late Permian to ?Triassic age (De Giusto and others, 1980, Andreis and others, 1987b).

Magallanes Basin

The Magallanes Basin is primarily a Mesozoic to Cenozoic basin located on the southern margin of South America. Poorly dated, thick Upper Palaeozoic turbiditic sediments (Bahia La Lancha Formation) and laterally equivalent low-grade metamorphics (Rio Lácteo Formation) occur in the northern part of the basin. Metamorphic grade increases from south to north; upper Palaeozoic granitoids, which include tonalites also occur in region. In the northeastern part of the basin sediments were deposited on metamorphic basement of the Deseado massif. To the west, the low-grade metamorphics were deposited on forearc oceanic crust or highly attenuated continental crust. Both formations have been deformed possibly as a result of sinistral, strike-slip faulting associated with the Gondwanide orogeny (Ramos, 1989a).

Choiyoi Province

The Choiyoi Province refers to an extensive region of Late Carboniferous to Triassic silicic plutonic, intrusive and extrusive igneous rocks that occur between approximately 25°S and 42°S in southern Argentina and eastern Chile, whose origin is not well understood. Most of Choiyoi Province in the southern region consists of Late Permian-Triassic rhyolites, ignimbrites and felsic plutons that possibly mark the culmination of the mainly Carboniferous Somuncura Batholith in northern Patagonia. Similar rocks in the northern region occur within the Late Palaeozoic magmatic arc that developed along the western margin of South America. The geochemistry of these igneous rocks suggest that they are a result of Late Palaeozoic-Early Mesozoic extensive crustal melting in a period of tectonic relaxation and extension that possibly occurred after cessation of terrane accretion and convergence (Hervé and others, 1987; Rapela & Kay, 1988; Kay and others, 1989).

Other Permian occurrances in the southern Andean region (7)

The Panguipulli Formation is of limited areal extent and is located at about 40°S in Chile. It consists of clastics with some olistostrome-like intervals, which developed on a subduction complex in a forearc position during the Permian; the sediments were derived from the east. The sequence was subsequently deformed into tight concentric folds, possibly in the latest Permian-Early Triassic (Forsythe, 1982; Hervé and others, 1981,1987; Uliana & Biddle, 1987). Along the present coast in the Madre de Dios area, minor exotic terranes have been identified (Mpodozis & Forsythe, 1983). The accreted material is composed of mafic and ultramafic oceanic rocks, and fusilinid platform-carbonates, associated with chert and flysch deposits. These terranes are similar to exotic terranes recognised in the North American circum-Pacific region and may represent a dispersed Palaeozoic Pacifica continent

(Ramos, 1988b). The 'Madre de Dios Terranes' probably accreted to the orogenic margin during the Triassic.

Isolated occurrences of Permian clastic and carbonate sequences up to 250m thick, which contain brachiopods and foraminifera, outcrop between 18°S and 32°S along the western orogenic belt. They were deposited on the recently accreted subduction complex or on Palaeozoic basement to the east (Azcuy, 1985; Hervé and others, 1987).

PALAEOGEOGRAPHY

The five accompanying palaeogeographic maps (Plates 2-6) represent a summary of the depositional environments present in Gondwana during each time slice interval, rather than a 'snap-shot' of a particular instant in time. The maps are generally non-palinspastic, consequently the configuration of the Gondwanan margin during the Permian was probably not as is represented in the palaeogeographic maps. This is due to tectonic processes operating around the margin, for example, active rifting of microcontinents along the Tethyan margin and transcurrent and thrust faulting along the southern Samfrau orogeny.

LATEST CARBONIFEROUS - ASSELIAN

The time slice 1 palaeogeographic map depicts the probable extent of the late Palaeozoic glaciation. This glaciation deposited subglacial, glacio-lacustrine, fluvio-glacial and glacio-marine sediments throughout cratonic areas of the Gondwana supercontinent. The age and scale of the glaciation is still subject to debate, although most workers tend to agree that the climax of glacial development was during the Late Carboniferous-earliest Permian, possibly Stephanian-Asselian. Recent work by Gonzálas (1990), in western Argentina, indicates that a long-lasting interglacial period may have occurred during the Stephanian

Glacial-marine diamictites in several western Argentinian basins are interbedded with fossils of the *Levipustula* zone of Middle-Late Carboniferous age (Lopez Gamundi, 1989). These basins vary from foreland to back-arc basins and the glacio-marine deposits are probably the result of mountain glaciation. No other region in Gondwanaland contains unequivocal glacial deposits of Middle Carboniferous age. Recent palynological data from the Gondwana glacial successions has failed to produce any evidence to support the idea that the Late Palaeozoic glaciation commenced in South America/South Africa and migrated across the supercontinent to India and Australia during the

Permian. However, these assemblages are from post or periglacial sediments, and must represent specialised facies (Truswell, 1980).

Although the age and extent of the Late Palaeozoic glaciation is arguable, for the purpose of this study I have compared the extent of the glaciation, based on presence of probable Stephanian-Asselian Gondwanan tillites, with that of the Pleistocene glaciation in the northern hemisphere (Fig 8). A palaeogeographical reconstruction of the Pleistocene glaciation was presented in Denton & Hughes (1981), which was based on the principle that if regional ice caps are continually nourished by moisture, coupled with low evaporation rates and cold climate, they will gradually coalesce to form a major ice sheet. Ice sheets are unstable and during warm interglacial periods or high-sea level they will disintergrate and retreat towards the centre of the original ice cap.

A comparison of the modelled dimensions of the Pleistocene and Late Palaeozoic glaciations shows that they were similar in latitudinal extent. The recently recognised Late Palaeozoic glacial sediments in the southern Arabian region were deposited at a relatively low palaeo-latitude and were probably derived from local montane sources. The northern African glacial deposits may have resulted from intraplate deformation associated with the Late Palaeozoic collision of Gondwana and the northern continents that reactivated pre-existing structures and produced locally elevated areas (Klitzch, 1986; Klitzsch & Squyres, 1990). However, the age control on these sediments is poor, and it is possible that they are products of the Ordovician glaciation in northern Africa (Caputo and Crowell, 1985).

Glacially derived sediments in Ethiopia and the southern Arabian region (Kruck & Thiele, 1982; Besems & Schuurman, 1987; Levell and others, 1988) are probably the products of an ice centre developed in the Yeman-Oman-Somalia region in an area of high relief. Alternatively, the extensive ice sheet developed in central Gondwana may have extended to the Arabian region, although the low palaeolatitude of the latter area and lack of evidence of glacial sediments in Kenya (Kreuser, 1984) argues against this hypothesis. Further north in the Arabian region, non-marine to possible littoral sediments of the Unayzah Formation, were deposited in an area not directly affected by glaciation. (al-Laboun, 1984, 1988).

<u>Africa</u>

Continental tillites and periglacial lacustrine sediments have been described in detail from the Ruhuhu Basin in Tanzania (Wopfner & Kreuser, 1986). Frakes & Crowell (1970) proposed that an ice centre was located in Zambia to the southwest and that a lobe of the ice sheet extended north to Tanzania and possibly eastward to Malagasy. The recent discovery of glacial sediments in Sri Lanka (Dahanayake &

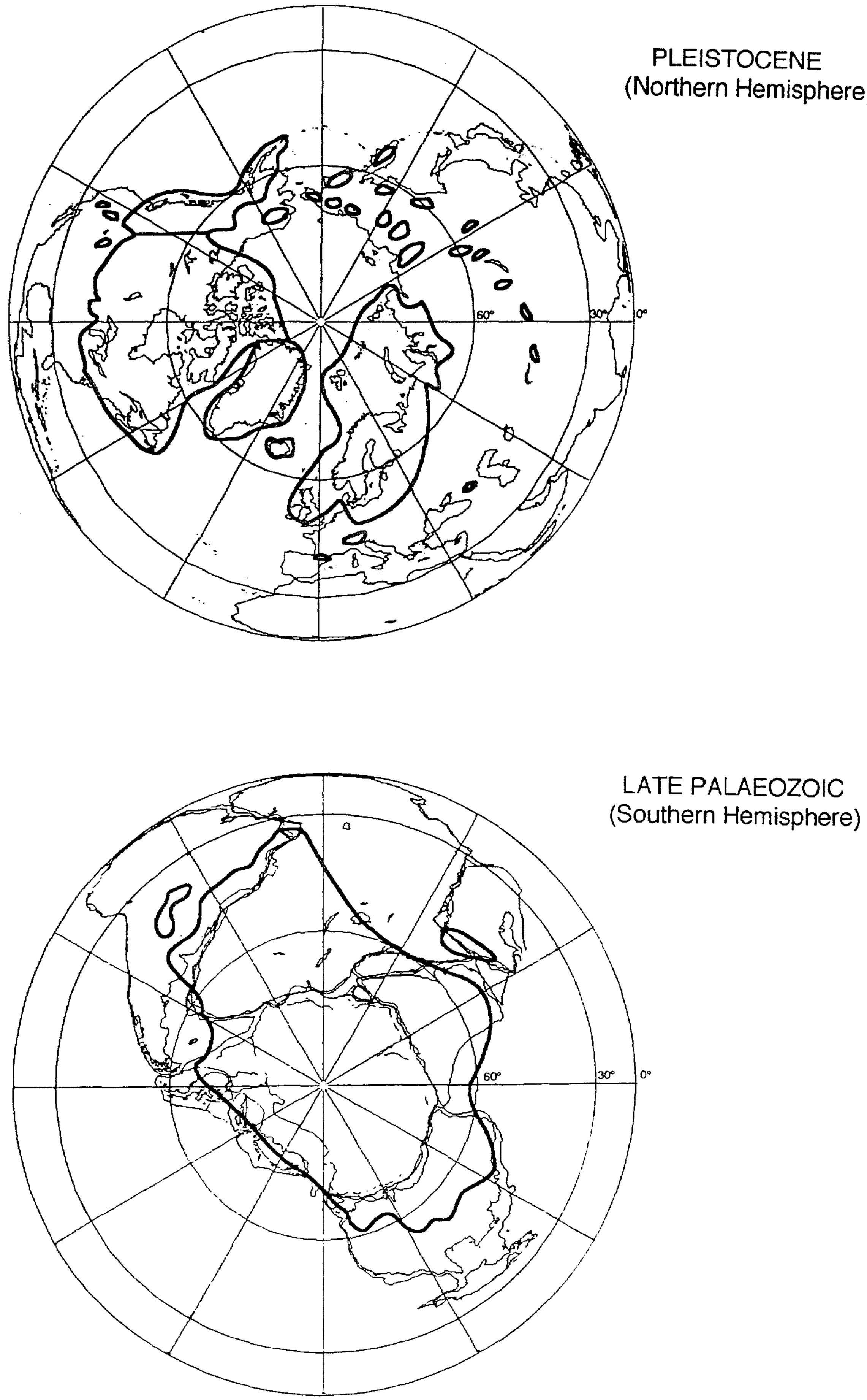

Figure 8. Extent of Pleistocene and Late Palaeozoic glaciation

Dasanayake, 1981) suggests that glacial environments were present south of Malagasy during the Late Palaeozoic and that equivalent glacial sediments may be present in western Antarctica.

Exhumed pre-glacial topography on the eastern margin of the Zaire Basin has exposed a number of palaeovalleys of unknown palaeo-relief, where glacial, periglacial and post-glacial sediments are preserved. It is likely that this upland region was covered with an ice cap which, in its waning stages, disintegrated into individual valley glaciers. The ice moved westwards into the centre of the basin and probably eastward into Tanzania (Martin, 1981).

Palaeogeographic studies in the Karoo and Kalahari Basins (Martin, 1975, 1981; Frakes & Crowell, 1975; Smith, 1984; Visser, 1983a,b, 1987, 1989) have shown that subpolar ice caps developed over highlands located to the north, east and south of the proto-Karoo Basin, and coalesced to form an extensive ice cover from the Westphalian to the Sakmarian. The palaeogeographic setting of the region may have been similar to the present-day Weddell Sea region between West and East Antarctica. Paleo-ice flow directions and isopach maps of preserved glacial sequences indicate that the ice sheet converged westward towards an open sea that extended northwards into southwest Gondwana and was probably connected to the palaeo-Pacific Ocean by a series of inlets in the southern highlands region. It has been suggested that this upland area may have been a mountainous island arc system or proto-Precordillera (Visser, 1987, 1989). Between four to nine glacial and interglacial stages have been recognised and abundant marine faunas, including *Eurydesma*, have been recovered from the Dwyka Formation and equivalents in the Kalahari and Karasburg Basins in Namibia.

Broad glacial-valley systems that dissected the Cargonian Highlands between the Karoo and Kalahari Basins and the Windhoek Highlands to the north of the Kalahari Basin (Visser, 1987), channelled ice away from the high interior region towards the west and south. Terrestrial valley, shelf and basinal glacial facies have been recognised in the region, although the latter facies form the bulk of the glacial sequence. Sedimentation on the continental shelf was initiated during a grounded ice sheet stage, by mainly lodgement processes, followed by debris rain-out and subaqueous debris flows during a floating ice-sheet stage , and finally suspension settling and debris rainout during disintegration on the ice sheet, probably in the early Sakmarian. Water depths varied throughout the region, although locally they may have been deeper (over 250m) than indicated on the accompanying palaeogeographic map.

In northern Africa the widespread Carboniferous marine inundation had receded and continental deposition occurred in a series of basins throughout the region. Sediment was sourced from the numerous basement highs that were reactivated during the crustal warping associated with the

Hercynian orogeny. Most of the basins appear to have had internal drainage systems except the Jeffra and Tehenu Basins on the southern margin of Tethys. Deposition in the interior basins was generally in fluvial and fluvio-lacustrine environments in a savannah-type climate.

In a series of intermontane basins in central Morocco, coarse grained clastics began to accumulate in fluvial systems in the higher relief margins of the grabens. Locally, red and grey mudstones, with thin carbonate and lignitic horizons, accumulated in flood-plain and shallow lacustrine environments in the centre of the basins. Volcanic activity in the region produced intrusions and locally massive outpourings of lavas and tuffs within the sediments. Floral studies have indicated that a dry tropical climate was present during the Early Permian in the region and both the sediments and biota have close affinities with western Europe (El Wartiti, 1990b).

Antarctica

Glacial beds have been identified in a number of localities along the Transantarctic, Pensacola and Ellsworth Mountains (Hambrey & Harland, 1981) above a major unconformity surface developed on Devonian sediments or crystalline basement. The glacial beds occur as sand dominated valley fill deposits, in sheets up to 300 metres thick, and as thick sequences of diamictite that increase in thickness eastward, up to 1000m (Barrett, 1991). Glacial beds are also present in Dronning Maud Land (Larsson and others, 1990), where a thin diamictite bed is overlain by varved shales containing acritarchs and the green algae *Tasmanites*, which indicates some marine influence within the sequence. The only reported glacial rocks in Western Antarctica are probable Late Palaeozoic diamictite boulders recently found in moraines in the Prince Charles Mountains (Webb and Fielding, 1991).

Studies indicate that the glacial sediments in the Transantarctic Basin were deposited from a continental ice sheet or series of sheets, where both dry and wet based conditions existed (Barrett and Kyle, 1975; Barrett and others, 1986). Between three to six major cycles of advance and retreat of the ice sheet have been observed within the Late Palaeozoic glacials, which range from 5 to 50 m thick. Much of the material deposited by ice was reworked by proglacial streams and lakes, although marine acritachs and thick sequences in the eastern part of the Transantarctic Basin indicate the presence of glacio-marine environments.

A major glacial centre in Victoria Land is evident from palaeocurrent and lithofacies associations (Crowell and Frakes, 1975). Ice flowed both norhward towards Australia approximately 1000 km away, and south-eastwards parallel to the the present Transantarctic Mountains, depositing sediment possibly as far as southern Africa (Visser, 1983). Northerly flowing glaciers in the northern Victoria

Land Basin eroded the basement to produce a series of valleys that were the site of an extensive post-glacial braid plain (Collinson and others, 1986).

Australia

Three major ice sheets have been identified in the Australian continent (Brakel and others, 1988); they may have joined together during glacial maximum periods. Floating ice shelves developed where the ice sheets discharged into the sea, eg. Canning, Carnarvon, Murray and Tasmanian Basins. Extensive terrestrial periglacial sediments are located in many of the Late Plaeozoic cratonic basins, where preservation is due mainly to post-depositional subsidence.

Latest Carboniferous to lower Permian sediments of the Kulshill Group are generally confined to the Petrel Sub-basin of the Bonaparte Basin. The sequence represents deposition in a reactivated rift structure that appears to have been derived from glacial activity to the south and possibly to the east of the basin. As the glacial influence decreased, an estuarine or lacustrine facies was deposited, followed by a fluvio-deltaic sequence. Seismic evidence suggests that up to 7000m of sediment may be present in the depocentre of the basin (Morey, 1988). To the northeast along the Irian Jaya shelf, latest Carboniferous-?Early Permian clastics and carbonates (Aimau Formation) were deposited in nearshore shallow marine environments (Dow and others, 1988).

On the eastern side of the Australian craton in the complex New England Orogen, deep water sedimentation, plutonism and volcanism, including arc volcanism, occurred (Day and others, 1983; Korsch & Harrington,.1981). Inboard of the orogen an extensive rift developed (Sydney-Gunnedah-Bowen basins) and a thick pile of bimodal volcanics was deposited.

New Zealand at this time was located at approximately 60° S and was part of an arc and forearc system developed offshore from the eastern margin of Gondwana (Bradshaw and others, 1981; Korsch and Wellman, 1988). There is no record of glaciation affecting New Zealand, although faunal evidence (Waterhouse, 1978; Archbold,1987) indicates that the seas in the region contained cold water organisms (Stevens, 1989).

India

In peninsula Indian, glacially derived sediments of the Talchir Formation, which resulted from the retreat of glacial lobes, accumulated in a series of reactivated linear basins; basin topography was the dominant controlling factor in sedimentation patterns. Lithofacies and palaeocurrent directions indicate that fluvial, lacustrine, shallow marine and estuarine sedimentation varied both spatially and temporally in the sub-continent in the Early Permian, and it appears that the latter depositional facies are more widespread than previously reported. Evidence also suggests that the Talchir sediments were derived from glaciers sourced from ice caps occupying the highlands in the proximity of various basins as opposed to a continental ice sheet (Robinson, 1967; Casshyap & Tewari, 1987). To the north in the present day Himalayan region glacio-marine facies equivalent to the Talchir Formation have been recognised in various localities along the entire chain of the Himalayas and in southern Tibet (Kapoor & Singh, 1987; Chang & Pan, 1984; Liu, 1989).

South America

Recent subsurface studies in the Paraná Basin indicate that three major glacial advances occurred in the latest Carboniferous to Early Permian (França and Potter, 1991). Terrestrial tillites were initially deposited in the centre of the basin, followed by a second glacial cycle associated minor marine incursions. The third and major depositional phase occurred during marine flooding of large areas of the basin, producing deep water conditions in the southern region and shallower conditions in the north. A wide range of depositional facies are associated with the glacially dominated Itararé Group, from deep water turbidites and varved shale, to debris flows and deltaic to shoreface sediments. The coastline was probably very irregular during various stages of deposition and the basin was surrounded by ice sheets to the west on the Asuncion Arch, to the east and possibly to the south. Major glacial lobes have been identified as the source of thick pebbly mudstones within the basin. Thin, very poor quality coal seams (<50cm thick) occur in the Itararé Group in the northeastern part of the basin, within interglacial fluvial-deltaic sequences; pre-*Gangamopteris* and *Gangamopteris* floras are also present in the carbonaceous units, in the lower and upper parts, respectively, of the glacial sediment (Rocha-Campos & Rosler, 1978; Martini & Rochas-Campos, 1988). Gas and condensate have been discovered within the glacial sediments of the Itararé Group.

Glacially derived sediment also occurs to the south in the Sierras Australes-Colorado Basin region and up to 1500m of clastics are present in the subsurface in the Chaco-Parana Basin (Hambrey and Harland 1981; Russo and others, 1980). It is uncertain whether glacio-marine deposition occurred in the latter area, although subaqueous conditions were definitely present during glaciation in the former region. Archangelsky and Azcuy, (1985) proposed that the Colorado, Chaco-Parana and Paraná Basins were connected during part of the Permian, and it is reasonable to assume that the marine transgression recognised in the Paraná Basin could have entered from the south.

In the northern part of South America cyclic calcarenites and evaporitic sequences were deposited in an extensive marine embayment (Amazon Basin), which was subjected to both marine and continental influences. Deltas deposited clastic material derived from the surrounding cratonic regions into the embayment. Changes in sea level and tectonic movements within the basin and along the proto-

Andean mountains temporarily restricted marine waters entering the basin and created lagoonal environments. To the east, thin fluvio-lacustrine sequences were deposited in the intracratonic Parnaiba Basin under warm temperate to semi-arid conditions.

Marine conditions were present along the western margin of South America and a marine barrier may have separated Patagonia from southern South America. Fluvial-lacustrine to marine sediments were deposited in a deep trough in Venezuela and and volcanic and plutonic activity occurred along the central and southern orogenic margin.

SAKMARIAN

Palaeogeography during the Sakmarian was dominated by the establishment of a series of marine or brackish water embayments which extended into the Gondwanan continent as a result of the melting of the continental ice sheet or ice sheets. Early Permian marine faunas that have been recovered from the Himalayas, Parana, Kalahari, Ventania, peninsula Indian and Australian basins, confirm the existance of widespread marine conditions. The rise in sea level is also evident in many other areas of Gondwana by the occurrence of trace fossils, acritarchs, pelitic facies and sedimentary structures within the Indian continental basins, the Karoo and Transantarctic Basin and other regions indicating that brackish water conditions were present during the period of widespread glaciation and immediately following glaciation (Dickens, 1975, 1980; Casshyap & Srivastava, 1987; Casshyap & Terawi, 1987; Rocha-Campos & Rosler, 1978; Visser, 1989; Lindsay, 1970; Barrett, 1991).

During the Sakmarian the central and eastern Tethyan margin was generally characterised by cold climates reflected in the low diversity of marine faunas. The cold water bivalves *Eurydesma* and *Deltopecten* have been recovered from many sequences along the Tethyan margin, indicating a strong Gondwanan element in faunal assemblages. These conditions were replaced by warmer climates later in the Early Permian (Dickens, 1977, 1985; Archbold, 1983). Similarly, cold water Sakmarian faunas are found in western India and eastern Oman and along the western Australian margin. Cold water conditions also existed along the eastern and southern margin of Gondwana, typified by faunas such as those from the Bonete Formation in eastern Argentina, the upper part of the Itarare Group in Brazil (Paraná Basin), and the Allandale Formation in the northern Sydney Basin (Rocha-Campos & Rosler, 1978; Dickens, 1977). Recent studies (J.M. Dickens, pers comm.) suggest that many of the Sakmarian faunas probably represent cool to possibly temperate water temperatures rather than cold water conditions.

In contrast to the cold water conditions found around the Gondwanan landmass, warm temperate to subtropical conditions were present during deposition of the shallow marine Copacabana Formation in Bolivia and southern Peru (Newell and others, 1953; Chamot, 1965; Wilson, 1990). Further to the north in Venezuela, subtropical to tropical waters supported a rich and diversified fauna in low latitude troughs (Arnold, 1966; Hoover, 1981).

Australia

Widespread bimodal volcanism in a back-arc extensional environment continued in the Sydney-Gunnedah-Bowen Basin system, with thick fluvio-lacustrine sediments including coal measures being deposited in the Denison Trough on the western margin of the Bowen Basin, and marine deposition in parts of the Sydney Basin. Coal swamps in the Reid Dome beds (Denison Trough) were dominated by articulates that grew in shallow-water areas adjacent to meandering streams; glossopterids derived material, which was generally allochthonous was a minor component of the coal swamps. Cool temperate to subpolar climatic conditions in the region inhibited aborescent plant growth (Draper & Beeston, 1985). Further south in the Tasmania Basin thin coals, which contain virtually no woody tissue were deposited in a wet, treeless moor environment (Bacon, 1986). Arc volcanism continued in eastern Queensland and deep water turbidities were deposited in extensional troughs in the New England Orogen. Active submarine volcanism also occurred in the allochthonous Gympie Terrane.

The ice sheet covering much of western, central and southern Australia retreated during the Sakmarian leaving only the central cores of the ice sheets (Brakel and others, 1988). On the outer and periglacial edges of the core areas terrestrial and glaciomarine sedimentation occurred in basins such as the Canning, Cooper and Perdirka Basins. Post-glacial sea level rise lead to the formation of a long, narrow seaway between Australia and Antarctica. Marine inundation also occurred along the western margin of the Australian continent locally depositing cold to cool temperate water carbonates. In the southern Perth Basin, thick coal measures deposition began within an extensive meridional trough, and continued throughout much of the Permian. To the north, in western Timor, clastics and carbonates were deposited by turbidity currents in an extensional trough; provenence studies suggest that the sediment was derived from the north of the trough (Bird and others, 1987).

Antarctica

In the Transantarctic Basin an easterly directed palaeoslope, i.e. towards the Ellsworth Mountains, prevailed throughout the Permian. A lag in isostatic readjustment after melting of the Late Palaeozoic ice sheet allowed for the deposition of a sequences of pro-deltaic, carbonaceous shale and thin bedded, fine grained sandstone (Mackeller Formation and equivalents) in a narrow restricted body of water. High strontium 87/86 ratios from a thin, less than 30 cm, limestone lens within the sequence indicate nonmarine conditions (Faure and Barrett, 1973). The environment of deposition has been likened to the present day Baltic Sea (Lindsay, 1970). Further downslope similar sediments were deposited, however a variety of trace fossils that have been recovered from these sediments, indicates more marine conditions in this part of the basin (Barrett, 1991). In the Ellsworth Mountains, thick sediments (Polarstar Formation) of similar age contain volcanic detritus at the base suggesting proximity to an active volcanic arc (Collinson, 1987). This association of dark laminated pelitic sediments overlying diamictites is a common feature of Early Permian sediments in many parts of Gondwana.

Small ice caps may have persisted at the end of the Sakmarian deglaciation, although the relatively rapid collapse of the ice sheet had led to the disappearance of most of the ice. Barrett (1991) suggested that uplift along the Pacific margin of Antarctica, associated with a reactivation of the Early Palaeozoic magmatic arc, may have created a "rain-shadow" effect, reducing moisture supply to the Antarctic ice sheet. The inferred ice centres in the middle and western margin of Antarctica are based on the premise that high altitude regions initially accumulate ice which if "nourished" will continue to develop as the centre of an ice cap. The presence of mountains in the interior of Eastern Antarctica, underneath the present day ice cap, is derived from interpreted sub-glacial topographic maps (Drewry, 1983).

India

At the end of the major glaciation and with the advent of a well-defined fluvial system, the Indian continental basins became unified into three linear basins, the northwest-southeast trending Mahandi and Godvari Basins, and the east-west trending Damodar and related basins. These linear basins became the site of fluvial sedimentation which continued throughout most of the Permian and Triassic.

Initially, coarse to medium grained sand and conglomerate with thin interbeds of shale and coal (Karharbari Formation) were deposited within braided and anastomosing fluvial systems. Facies analysis of the Karharbari Formation (Casshyap & Tewari, 1984, 1987) indicates that periodic uplift and rapid subsidence prevented the development of thick peat swamps, producing only thin, non-persistent and split coal seams. Marine transgression during the Karharbari is evident from the occurrence of brackish water acritarchs within sediments deposited in the lower reaches of the river systems (Banerjee, 1987).

During the Tastubian, a marine transgression entered central India from the west, possibly along the Narmada Valley, and deposited sediments containing brachiopod and molluscan faunas, including *Eurysdema*, that are similar to faunas in the Salt Range and along the margin of Tethys (Sastry & Shah, 1964). An earlier Asselian, or Lower Tastubian, transgression may have occurred in India, possibly entering from the north, ie; eastern Himalayas (Shan and Sastry, 1975, Chatterjee & Hotton, 1986), flooding the Koel-Damadar Valley basins; however the exact age control of many of the Indian Early Permian faunas (and other Gondwana faunas) is still conjectural (Archbold, 1982). Along the Indian Tethyan margin of Gondwana, volcanism in the Zanskar and Arunachal Pradesh regions (Bhat and others, 1981) records the initial rifting associated with the formation of Neo-Tethys.

Further to the southwest in Malagasy, coarse sandstones and conglomerates were deposited on a sequence of tillite and shale, which were in turn overlain by a sand-rich, coal bearing sequence in the southern region of the Morondava Basin. Thin detrital coal deposits overlying post-glacial marine sandstone have also been reported in the Salt Range sequence in Pakistan (Ahmed and others, 1986).

Africa

Post-glacial flooding of large areas of southwestern Gondwana can be attributed to a combination of post-glacial sea level rise and isostatic subsidence resulting from the weight of the ice and increased sediment load (Visser, 1987). Remnant ice caps probably persisted in the highland regions to the north of the Karoo Basin; basinwards locally fossiliferous shales of the Pietermaritzburg and Prince Albert Formations accumulated. In the northeast corner of the basin, glaciofluvial and minor glaciolacustrine sequences were overlain by peat swamps that began to develop within braided fluvial systems in glacially scoured valleys (Cairncross, 1989).

Marine environments that were present in the western part of the Kalahari Basin were gradually infilled by pro-delta muds derived from the basin margins. To the northeast, in the gently undulating landscape of the Zambezi Basin region (an average of 150m vertical relief), glacial material was reworked and re-deposited by melt-water streams. Basin subsidence appears to have been initiated by the Sakmarian and gradually, arenaceous material began to fill the lakes where carbonaceous matter had previously accumulated (Travener-Smith, 1960). To the north, in the Ruhuhu Basin in Tanzania melt-water from the waning glaciers was deposited in fluvial to lacustrine environments, with the lakes remaining after the final retreat of the ice. Sediment was sourced mainly from the west and northwest, and was deposited in rivers to form cyclic sequences that generally commenced deposition in braided stream environments, changing to higher sinuousity meandering stream systems that were associated with mudstone/peat facies. The regional climate had changed from the glacial period to a semi-humid boreal climate with prolific coal swamp development (Kreuser and others, 1990).

Arabia

Predominantly non-marine, mainly clastic sediments were deposited in the Arabian region, however, a marginal-marine incursion associated with the post-glacial sea level rise may have occurred in the southern region and possibly in the northwest. Braided streams associated with the southward retreating ice cap (glaciers) in the Oman area infilled deep valleys and deposited locally thick clastics which now form oil reservoirs of the southern Oman oil fields (de la Grandville, 1982; Levell and others, 1988). A large, fresh to brackish water body (Rahab Shale) developed with the disappearance of the ice cap over much of southern Oman; minor occurences of *Tasmanitids* and acritarchs (*Deuselites*) suggest marine influence.

South America

Widespread marine conditions continued along the western South American orogenic margin and, in basinal regions adjacent to the palaeo-Pacific, estuarine and deltaic sediments were deposited. Glacio-marine sedimentation in the Paraná Basin was followed by climatic amelioration and the development of coal measures (Rio Bonito Formation) along the eastern margin of the basin, a process that continued into the Artinskian. Most of the coals in the south, i.e. Rio Grande du Sul, were deposited within palaeovalleys in limno-telematic peatlands, although other coal seams are associated with deltaic and barred coastline facies. The coal seams to the north appear to have formed in predominantly fluvial-deltaic sequences (Machado, 1975; Corrêa da Silva and others, 1984; Martini and Rocha-Campos, 1988). The Rio Bonito Formation represents three distinct depositional periods, a basal fluvial-deltaic sequence, followed by a transgressive sand associated with pro-delta and delta front facies; a middle depositional period during which thin carbonate platform deposits formed in interdeltaic regions; the final phase when strandplain and barrier-lagoon systems were well developed in the southern part of the basin (Medeiros and Filho, 1973; Soares and Cava, 1982).

ARTINSKIAN-KUNGURIAN

Climatic warming along the northern margin of Gondwana during the Artinskian eliminated the strong Gondwanan element of faunas and increased the Tethyan aspect of the region (Dickens & Shah, 1980; Archbold, 1987). On the western side of Gondwana, in the Peru and Bolivia region, warm to subtropical conditions continued. Water temperatures in southwestern Gondwana were probably cool during this time interval, associated with the amelioration of glacial conditions, although the meagre faunal assemblages in this region are poorly understood.

The eastern Australian region continued to be influenced by cold and cool temperate waters, however by the late Early Permian a north-south differentiation into a cold water regime that persisted in Tasmania and somewhat warmer (cool temperate) regime to the north in the Bowen Basin in Queensland. In contrast, temperate conditions developed in western Australian waters, which were associated with faunas with stronger affinities to those in Tethys (Dickens, 1978). Consequently, a west-east climatic gradient probably also existed across the Australian continent.

Australia

By the Artinskian, ice caps and glaciers had receded from the Australian continent, except to the west of the Sydney Basin and possibly in western Victoria, where valley glaciers locally re-appeared; the age of sediments in the latter locality is not well constrained. The seaway between Australia and Antartica also disappeared and marine conditions were restricted to the Tasmanian Basin. Widespread coal measure deposition occurred throughout most of the Australian region in mainly fluvial, fluvio-lacustrine or paralic environments (Brakel & Totterdell, in prep).

Deposition in most of the interior basins appears to have ceased, except in the Cooper Basin where an extensive lake developed fringed by fluvial-deltaic complexes, where thick coal measures accumulated (Thornton, 1979). Marine conditions, associated with transgressive phases, continued along the western and northwestern margin and a large delta built out across the Carnarvon Basin. Tectonism south of the Fitzroy Trough in the Canning Basin caused the local emergence of the underlying Broome Arch (Yeates and others, 1984).

Marine and marginal marine conditions were established in the Sydney, Gunnedah and Bowen Basins. Thick peat swamps locally developed in fluvial, fluvio-lacustrine, deltaic and paralic environments. Compressive tectonism along the eastern margin of the basins, initiated in the ?late Artinskian, caused local graben inversion and a change in structural development from an extensional to a foreland basin setting (Mallet and others, 1988). Volcanism, plutonism and locally deep water sedimentation continued in the New England Orogen.

Frakes (1979) postulated that southward-flowing warm to tropical oceanic currents from the Tethyan region brought warm waters to the eastern shore of Gondwana. Evaporation from these warm water over the cold landmass to the west presumably caused high precipitation which probably decreased inland. The high humidity formed terrestrial mires over much of the Australian continent where thick peats developed, analogous to modern high-latitude mires (Martini & Glooscenko, 1985). An overall regional variation from inertinite-rich coals in freshwater cratonic areas, (e.g. Cooper and Gallilee Basins) to vitrinite-rich coals in the Sydney-Gunnedah-Bowen basins has been well documented (Hunt, 1989). Subsidence rates during peat accumulation was probably the main controlling regional factor on vitrinite content; lower subsidence rates in the cratonic basins caused extensive oxidation of the peat (Hunt & Smyth, 1989). However, local changes in vitrinite/inertinite content may reflect regional precipitation pattern, periods of marine influences and associated water table fluctuations;

India

Sedimentation continued in the Indian continental basins (Barakar Formation), however there was a change in fluvial style from a braided system at the base of the unit, to moderately sinuous and finally meandering in the upper part of the formation. Palaeocurrent directions indicate that the major rivers flowed with a gentle palaeoslope from southeast to northwest. The lack of active faulting is reflected in the composition of the resultant sediments with a progressive decrease in channel sands and increase in fine clastics in a downcurrent direction, as well as an absence of conglomeratic horizions. The topography source area appears to have matured since the Talchir glaciation due to prolonged erosion in a cold and wet climate (Casshyap & Tewari, 1987).

The basins appear to have expanded areally during this period, locally overlapping the underlying basement, to accomodate the thick (200-1000 m) cyclic accumulation of clastics and coals of the Barakar Formation. The thick, laterally continuous coals were deposited in protected peat swamps in distal flood plains and lakes (Casshyap & Tewari, 1984). A marine influence on sedimentation is indicated by diverse acritarch assemblages (Venkatachala & Tiwari, 1987; Banerjee & D'Rozario, 1990) in many of the Indian grabens, and the presence of foraminifera in shales and compressed *Glossopteris* leaves within the coal measures (Banerjee, 1991).

The widespread marine shelf along the Indian Tethyan margin was locally raised above sea-level, as evidenced by the occurrence of the plant-bearing Nishatbagh Formation and lagoonal Mamal Formation in the Kashmir region. Cathaysian-related floral elements are found together with typical Gondwanan floras indicating the presence of a probable floral transition zone in the area. Thick volcanic flows (Pangal Volcanics) filled the Neo-Tethys rift valleys in the northwest Himalayan area, and to the west, in northern Oman, submarine volcanics attest to the regional nature of rifting along the Gondwanan margin.

New Zealand

Land areas in New Zealand throughout the Permian were probably ephemeral in nature in the form of volcanic islands and archipelagoes. Nevertheless, the New Zealand biota had close links to Australia, Tasmania and Antarctica; eg. *Glossopteris* fragments have been observed as detrital elements within sediments (Stevens, 1989). Coal analyses on Permian coalified wood indicates the material is semi-anthracite in rank due to post-depositional metamorphism (Suggate, 1990).

Antarctica

In South Victoria Land glacial sediments are disconformably overlain by a sequence of coal measures (Weller Coal Measures) up to 250 metres thick, with individual seams up to 7m thick. In general, these sediments show easterly directed palaeocurrents. Facies analysis (Pyne, 1986) indicates that these coal measures were deposited in braided and meandering fluvial systems which may have formed the headwaters of the Transantarctic Basin. Further downslope in the Transantarctic Basin, braided fluvial sediments (Fairchild Formation and equivalents) were deposited over the paralic and pro-delta sediments of the post-glacial sequence. These sediments were subsequently overlain by a locally thick accumulation of coal measures (Buckley Formation and equivalents) in what appears to be a dominantly meandering stream system that continued into the Late Permian (Elliot, 1975; Barrett and others, 1986, Barrett, 1991). Felsic volcanic detritus within the sequence indicates coeval magmatism, probably sourced from the proto-Pacific margin of the basin. Pervasive, post-depositional Jurassic volcanism destroyed palynomorphs in the coal measure sequences, thereby hindering accurate depositional age determination. Natural coke has also been recovered from coals in close proximity to igneous intrusions.

In the northern part of North Victoria Land, a sandy braided fluvial system deposited coarse grained material in alluvial fans on the margins of a graben and carbonaceous material in the axis of the trough (Collinson and others, 1986). This northward flowing alluvial valley may well have contributed sediment to the nearby Tasmania Basin.

Africa

Fluvial peat swamps developed in many of the basinal regions in southern Africa, from the Zaire Basin in the north to the Karoo Basin in the south. In the northeastern Karoo Basin, deposition of locally thick coals and clastics of the Vryheid Formation continued in confined narrow palaeovalleys. Further south and southeast, a coal-bearing succession began to accumulate in fluviodeltaic and paralic environments on broad featureless plains, composed of post-glacial shelf deposits. Basinwards, shallow marine conditions were present.

Coals that developed in lower delta plain environments are generally thin (<1m), laterally non-persistent (approximately 10km in width) and relatively high in vitrinite; coals formed in fluvial and upper delta plain environments are thick (2-20m), laterally extensive (10-150km) and have higher inertinite and lower vitrinite contents than those formed in lower delta plain environments. The distal edge of peat development, in places defined by palaeoshoreline sequences, was periodically breached, as basinwide transgressions terminated peat accumulation and deposited glauconite-rich sediments. Coal rank increases southwards due to the increased subsidence rates and associated higher geothermal gradient (Tankard and others, 1982; Cadle and others, 1990).

At the end of the Early Permian, the relatively thin organic rich shales of the Whitehill Formation were deposited in the central and southern parts of the Karoo Basin. The unit is fossiliferous containing mesosaurid reptiles *Mesosaurus* and *Stereosternum*, which are also found in equivalent black shales in the Karasburg and western Kalahari Basins, as well as in the Paraná Basin in Brazil, where it forms one of the largest oil shale deposits in the world. This fossil evidence suggests that these basins formed contemporaneous anoxic embayments in the two continents and were part of a single extensive basin that may have been connected to the palaeo-Pacific Ocean to the south (Oelofsen, 1987). Remnant ice caps may have been present in highland regions, although there is little direct evidence for their presence (Visser, 1989, 1990).

The post-glacial lacustrine to lagoonal deposits in the Kalahari Basin are overlain by laterally persistant fluvial sandstones, which were deposited as a result of uplift on the basin margins. A locally swampy fluviodeltaic system was established over much of the basin especially in the southwest, and peat began to accumulate locally (Smith, 1984). To the northeast in the Zambezi Basin area, peat continued to accumulate in fine grained sediments on shorelines surrounding freshwater lakes (Rust, 1975; Duguid, 1986b). Coal seam splitting and interbedded arenaceous units indicate tectonic instability in the region (Reimann, 1986). Peat also continued to accumulate in Tanzania although, possibly near the end of this time slice interval, the climate changed to a semi-arid, warm to possible hot climate. Sediments were then deposited under oxidising conditions in a flood plain-playa environment with influxes of fluvial sheet flood clastics. Further northwards, towards the palaeo-equator in Gabon, Early Permian carbonaceous shales were gradually overlain by evaporites in a restricted basin. Deposition in many of the Permian basins along the northern margin of Africa terminated at the end of this time interval.

Malagasy

Coal deposition in ?limnic environments probably continued from the previous time-slice interval (Sakmarian) in the southern part of the Morondava Basin. The coal beds are overlain by red shales and arkosic sandstones containing reptilian faunas and silicified wood, which are more widely distributed than the coal bearing beds; the age control on the latter unit is poor. These oxidised sediments are similar to sediments in Tanzania to the west and may indicate an increase in seasonality possibly due to the onset of monsoonal conditions. A marine barrier may have existed between Malagasy and eastern Africa (Radelli, 1975), and fluctuations of sea level would certainly have influenced local climate on the margins of the embayment.

Arabia

Plant material and very thin coals accumulated locally in swampy environments during the Late Carboniferous-Early Permian in the northwestern Arabian area (Bege, 1986). By the end of the Early Permian the major marine transgressive phase of the Late Permian was initiated with marine waters entering the southeast region (Murris, 1980; Sharief,1982). In northern Oman, marine conditions were established, possibly concomitant with rifting in the Hawasina Basin; tholeiitic volcanism associated with crustal thinning may also have started late in the Early Permian (Robertson and Searle, 1990; Blendinger and others, 1990).

South America

Peat formation continued in the Paraná Basin in fluvial-deltaic and strandplain, and barrier-lagoon facies environments. Most of the resultant coal seams are relatively high in ash, are generally less than 2-3m in thickness and range from subbituminous to bituminous in rank. Transgression of a shallow sea terminated coal development in the basin and deposited the mainly sandy siltstones of the Palermo and Tatui Formations across large areas of the basin. Sedimentary structures and abundant worm-type burrows in the Palermo Formation suggest deposition in sub-tidal to inner shelf environments, although neither open marine megafossils, or any other conclusive evidence to suggest marine deposition have been reported from the transgressive unit (Bigarella and others, 1967; Machado, 1975). At the end of the early Permian, or possibly during the early Late Permian thin clastics and bituminous shales with limestone intercalations of the Irati Formation were deposited throughout the basin in marine to brackish water environments.

By the late Early Permian the Amazon Basin had been cut off from the proto-Pacific Ocean to the west and a series of disconnected salt lakes were present. Aridity increased during the late Early Permian along the western margin attested by the presence of aeolin and fluvial deposits in many of the basins in the region, such as in the Paganzo Basin (Limarino & Spalletti, 1986). This was probably a result of an emerging volcanic arc along the margin that acted as a topographic barrier to the west of the marginal basins, creating a 'rain-shadow'. Humid micro-environments along the southern margin of the Tarija-Titicaca Basin deposited thin, paralic coal beds and clastics (Cousminer, 1965; Helwig, 1972).

UFIMIAN - KAZANIAN

Water temperatures along the Tethyan margin varied from tropical to sub-tropical, as indicated by high faunal diversity. There was a cool temperate to temperate temperature gradient from south to north in eastern Australia; ice-rafted dropstones, probably deposited from seasonal pack ice, have been reported from the Tasmanian Basin (Banks and Clark, 1987). Endemic bivalve faunas from the Paraná Basin (Runnegar & Newell, 1971) are probably not quite as endemic as initially thought (J.M. Dickens, pers comm.), however palaeoclimatic conditions in southwest Gondwana are as yet not well understood. Marine to brackish water conditions were widespread throughout many of the marginal Gondwana basins, although by the end of the Kazanian a regional (and global) regressive phase was initiated.

<u>Arabia</u>

The Arabian region was inundated by an extensive marine transgression, and thick warm-water carbonates, including reef and evaporite facies, were deposited in a semi-arid climate, from Oman in the south to Iran in the north (Moullade & Nairn, 1978, Murris, 1980). The coastal hinterland was subject to laterization while thin, poor quality coal measure sediments developed locally under paralic conditions along the western margin of the basin (Bege, 1986). In northern Oman a carbonate shelf-slope sequence was established with deposition of fine grained sediments on a substratum of mafic pillow basalts and volcaniclastics in the centre of the Hawasina Basin.

<u>Australia</u>

A rise in sea level inundated the Sydney-Gunnedah-Bowen trough to form a continuous seaway inboard of the New England Orogen, which was the site of active tectonism, plutonism and related ignimbritic volcanism (McPhie, 1986, 1988). The accompanying palaeogeographic map depicts the regression following the formation of the seaway when the foreland Gunnedah and Sydney Basins began to be infilled with fluvial and deltaic coal measures, derived in part from the adjacent uplifted highs. To the south, in the Tasmanian Basin, marine conditions continued, although at the end of the Kazanian, a retreat of the sea led to the formation of an offshore barrier bar facies in southern Tasmania.

In contrast, the extensive marine conditions of the Early Permian in the Canning Basin were replaced by mainly lagoonal deposits and local deltas, with minor peat swamps in the Fitzroy Trough, although in the Carnarvon and Bonaparte Basins, transgressive phases occurred. A large delta complex began to build out across the Bonaparte Basin at the end of the Kazanian (Brakel & Totterdell, 1988), and it also appears that regressive conditions began in Irian Jaya along the northern margin of the Australian craton.

<u>India</u>

A relative rise in temperature and possibly increased seasonality in the Indian region was reflected by deposition of the Barren Measures and time-equivalent units, which are composed of grey, brown to locally red clastics and contain no workable coal measures. The age of the Barren Measures is not well constrained due to problems in palynological correlations between Australia and India. However floral studies (Chandra & Chandra, 1987; Tiwari & Tripathi, 1987) have shown that appreciable vegetation covered the region; oxidation of organic material due to climatic fluctutation and/or subsidence rates and associated water table movements would explain the lack of coal measures. Depositional facies varied within the Indian grabens from dominately lacustrine in the Koel-Damodar region, to fluvial dominated in the more continental Maranadi and Godvari regions; recently, possible marine influences in the northern sequences has been proposed by Casshyap & Tewari, (1987) and Venkatachala & Tiwari, (1987). Rifting continued in the Himalayan region to the north.

Antarctica

In the Prince Charles Mountains, a broad alluvial plain, with an axial drainage system was established in the Lambert Graben and a thick sequence of coal-bearing clastics was deposited by a northerly directed braided river system. This alluvial system may well have continued into peninsula India, connecting with rivers in the Son-Maranadi graben. Most of the coal seams in the Lambert Graben are less than one metre thick, although some seams are over five metres thick. There is no evidence of Jurassic dolerites in the region and consequently coal rank in the area is bituminous, in contrast to the low volatile, semianthracite rank of coal seams in the Transantarctic Mountains (Rose & McElroy, 1987).

Coal measure sediments continued to fill the elongate Transantarctic Mountain Basin, which had a regional palaeoslope directed towards South Africa. In the eastern headwater region of the basin, local tectonic activity, possibly related to a resumption in regional subduction (Barrett, 1991) appears to have moved the basin divide eastward, creating separate depositional basins in the South and North Victoria Land Basins.

Malagasy

Marine incursions have been recognised in the upper part of the Sakoa Group, which underlie the shallow marine Vohitolia Limestone in the Morondava Basin. The *Productus* bearing limestone is less than 30m thick, and contains various facies including oolitic and reefal carbonates. Following deposition of the Sakoa Group, tectonic movements possibly associated with rifting formed a major unconformity surface with the overlying Sakmena Group and produced horst and graben structures within the basin (Boast & Nairn, 1982, Radelli, 1975). Further north, in the Diego Basin, marine conditions were locally established and clastics that are probable lateral equivalents of the Vohitolia Limestone were deposited.

Africa

Peat swamp deposition continued or resumed in many of the rift and intracratonic basins in southern Africa. Increased subsidence rates in the Karoo Trough, probably due to thrust loading of the Cape Fold Belt, allowed the accumulation of up to 2000m of a regressive turbiditic to deltaic sequence (Upper Ecca Group). Water depths were up to 500m during the initial deposition of the turbidite sequence (Visser & Loock, 1978, Smith, 1990). To the north of the basin, fine-grained clastics and very minor, thin coals of the Volkrust Formation were deposited in shallow water and paralic environments during regional transgressive-regressive events (Travener-Smith and others, 1988); lacustrine conditions may have also existed within the basin during Upper Ecca Group deposition (Smith, 1990).

Over broad areas of the central Kalahari Basin subsidence was slow and river-dominated deltas built out into shallow water, forming a widespread swampy flood plain. The vegetation on the flood plain probably consisted of a poor reedy flora that trapped fine grained sediment resulting in thin peat and mud deposits. Thicker, better quality coals formed in the southeast within fluvial sandstones or in grabens near the margins of the basin (Smith, 1984; Clark and others, 1986). Peat accumulation resumed in Tanzania with an increase in humidity, possibly due to the presence of a marine embayment to the east in the "Malagasy Trough". Deposition of coal occurred in shallow lacustrine systems in a warm climate associated with a period of tectonic stability; the resultant coal seams are generally thin, non-persistent and of a poor quality (Kreuser and others, 1990). Many of the rift basins of southern Africa were filled with grey-green mudstones that accumulated in a series of large lakes, in areas of steady gentle subsidence. These are typified by the Madumabisa Mudstone in the Mid Zambezi Basin (Yemane & Kelts, 1990).

South America

The Late Permian sediments of the Passa Dois Group in the Paraná Basin were deposited in an expansive shallow epicontinental sea, subject to considerable evaporation under apparently tectonically stable, semi-arid to arid conditions. The depositional setting of the various units within the Passa Dois Group is controversial (Bigarella and others, 1967; Fulfaro & Landim, 1976; Mello Sousa and others, 1988; Sohn & Rochas Campos, 1990), however, evidence suggests that the Serra Alta (lower Estrada Nova Formation) was deposited in offshore environments whereas the Terezina Formation (upper Estrada Nova Formation or Teresina Formation) was deposited in a prograding tidal flat environment. To the north and northwest of the basin, fine clastics of the Corumbatai Formation were deposited in intertidal to lagoonal environments. The presence of nonmarine ostracodes in the Corumbatai Formation suggests that rivers flowed into the basin from the north lowering salinity of the water along the basin margin. The location of a seaway entrance into the basin is also uncertain, however regional considerations suggest that brackish waters may have entered the basin fom the east. Coal deposition had ceased in the basin.

Widespread tectonic activity along the orogenic margin during the mid Permian (Tardihercynian and Ranrafaelic orogens) resulted in the formation of erosional unconformities in several basins in the region (Azcuy, 1985). Semi-arid to arid continental conditions continued to dominate the central and southern margin resulting in the local deposition of red beds, aeolin sandstones and evaporites. Explosive volcanism and plutonism occurred within magmatic arcs and in extensional environments from Peru in the north to Patagonia in the south.

TATARIAN - DORASHAMIAN

This time interval represents the period of lowest sea level during the Permian in Gondwana; non marine conditions were widespread in all of the major Gondwana basins, except for the marginal Tethyan basinal areas. Distinctive faunas of subtropical to tropical affinities are present in sediments from the northwest of Australia (Canning and Bonaparte Basins). These faunas have strong links to similar Tethyan faunas (Chhidruan) found in the Himalayas and the Salt Range in Pakistan, and it is the only definitive evidence of warm water in the Australian region during the Permian (Dickens, 1978, Archbold, 1987). Climatic conditions in western Gondwana were generally warm temperate to semi-arid and locally arid.

Australia

At the end of the Permian continental deposition dominated the Australian craton. The major regressive phase in the Sydney-Gunnedah-Bowen Basins continued in the subsiding foreland trough and resulted in the deposition of thick coal measures and detritus mainly derived from the active New England Orogen to the east. Local volcanic activity in the orogen produced tuff that is locally interbedded with coal measures; in the northern Sydney Basin coal seams (Wollombi/Newcastle Coal Measures) are locally interbedded with fanglomerates and tuffs. Extensive peat swamps that were precursors to many economic coal deposits, (i.e. Blackwater Group, Illawarra Coal Measures) developed over the eastern half of the continent in cool temperate, poorly drained, fluvial, fluvio-lacustrine and fluvial-deltaic depositional environments (Herbert & Helby, 1980; Hobday, 1987; Brakel & Totterdell, 1988, in prep; Fielding and others, 1991).

The southeasterly directed regressive phase in the Tasmanian Basin was followed by prograding sandy flood plain deposition including minor peat swamps. By the end of the Permian, high-sinuousity rivers were established over most of the basin (Banks & Clarke, 1987); fluvial sediments derived from North Victoria Land may have formed part of this extensive fluvial plain.

To the northwest, fluival-deltaic environments were re-established in the Bonaparte Basin where thin peat deposits accumulated behind a prograding barrier bar. Further south in the Carnarvon Basin emergent conditions were widespread and coal (Sue Coal Measures) continued to be deposited in the subsiding south Perth Basin.

India

An apparent increase in both precipitation and temperature produced a local resumption in coal deposition in several basins in continental India (Tiwari & Tripathi, 1987). The coals occur as thin to moderately thick seams, laterally continuous for tens of kilometres, and are interbedded with subarkosic to arkosic arenites in dominantly meandering fluvial facies. One seam in the Singrauli Coalfield in the Son Valley Basin is approximately 160m thick, although the ash content varies from 30 to 35 per cent. The palaeodrainage direction in the unified basins was to the northwest and west, and the relatively flat topography and proximity to shorelines in the north may have resulted in periodic marine incursions (Casshyap & Tewari, 1987). In the more interior basins deposition occurred in more arid oxiding environments. In the Rajmahal Basins area, sedimentation was considered to have ceased after deposition of the Early Permian Barakar Formation, however recent palynological studies (Prasad, 1985; Tripathi, 1986) have shown that Raniganj Formation equivalents are present in the region.

In the northwest Himalayan region volcanism (Panjal Traps) had ceased and a widespread transgression deposited locally calcareous marine sediments along the Tethyan margin. Warm-water faunas from the Himalayas are remarkably similar to faunas found in Western Australia indicating their close proximity (Archbold, 1987). Further to the north in the Karakoram region, rapid subsidence during the latest Permian (Gaetani and others, 1990) led to the deposition of deep-water carbonates as a result of the northward rifting of the Karakoram microplate.

Antarctica

Coal measure deposition may have continued in the Lambert Graben in the Prince Charles Mountain area, however by the latest Permian, rainfall activity decreased and the vast floodplains adjacent to the river dried out forming dessicated mud-flats and causing the disappearance of the peat swamps. The river system continued to be active during the Triassic with fern-like *Dicroidium* and small conifers growing along the river channels (Webb & Fielding 1991).

Tectonic activity associated with the Gondwanide Orogeny uplifted the the western area of the Transantarctic Basin (Ellsworth Mountains), resulting in a regional reversal of palaeoslope. Coal deposition probably continued in the basin that probably had an internal drainage system. During the latest Permian coal measure deposition decreased and, following a period of regional non-deposition, the basin was filled by Triassic volcanic-rich, alluvial material (Elliot, 1975).

Africa

Lower Beaufort and equivalent sequences (late Late Permian) in central and southern Africa vary in thickness from over 1000 m in the southern Karoo Basin to a few metres in central Africa. The sequences are dominated by lacustrine, fluvial and fluvio-lacustrine facies except in eastern Tanzania where marine influences have been reported (Cox, 1935, Kreuser, 1984b). The latest Permian palaeogeography of southern Africa was dominated by a series of large lakes that were locally inundated by flood-plain deposits (Rust, 1975). The basins were situated in the same palaeolatitude belt and consequently contain similar lithofacies and faunal assemblages, notably mammal-like reptiles (therapsids), which indicate moderately warm and moist conditions of a monsoonal climate (Parrish and others, 1986; Yemane & Kelts, 1990).

The shrinking Karoo Basin was occupied by a series of lakes in the north and east of the basin whereas in the south, adjacent to the tectonically active mountain belt, a molasse type wedge of fluvio-deltaic sediments prograded across the lacustrine shelf (Hobday, 1978). Ephemeral sheet-flood and semi-permanent lake deposits that have been identified in the southwestern area of the basin formed in response to the semi-arid, seasonal rainfall (Stear, 1983, Smith, 1990). Further north in the Kalahari Basin, broad internal lakes were present; those in the north of the basin containing calcareous beds probably were warm, shallow water, seasonal lakes, whereas in the central part of the basin a large lake, or lakes received fine grained clastics derived from the south (Smith, 1984).

Greenish-grey, calcareous lacustrine sediments (K5), overlain by red, maroon and grey, locally calcareous clastics (K6), are present in the Ruhuhu Basin in Tanzania (Kreuser & Martwort, 1989), and similar thicker sediments were recorded in Zambia and Zimbabwe (Madumabisa Formation - Falcon, 1975) and Kenya (Lower Maja-ya Chumvi beds). The upper part of the sequence in the Ruhuhu Basin contains dessication cracks, raindrop imprints and septarian nodules, indicating a playa environment that reflects increasing aridity in the latest Permian. Detailed sedimentological studies in Malawi (Yemane and others, 1989) indicate the presence of an ancient freshwater lake that was deposited in an area of significant topographic relief; this is equivalent to other sequences in southern African basins, but differs in that no sub-aerial depositional features were recorded.

Malagasy

Further east in Malagasy marine conditions existed in the north. In the Morondava Basin to the south fluvio-lacustrine environments were present, although brackish conditions probably existed in the western part of the basin. Gymnosperm-dominated vegetation, with presumed arid-semiarid elements (eg. *Weylandites*) and few moisture-loving cryptogams (eg. ferns), flourished in southern Malagasy, however the diversity was lower than in other areas in the region. Vegetation changed at about the Permo-Triassic boundary with marine flooding from the north, as evidenced by an influx of marine microplankton, and the Morondava Basin was colonised by a coastal lycopod flora (Wright & Askin, 1987).

South America

Deposition of the regressive upper Corumbatai and upper Terezina Formations probably continued into the Tatarian, however age control in the upper part of the Paraná Basin Permian sequence is generally poor (Sohn and Rocha-Campos, 1990). The Rio da Rasto Formation conformably overlies the Terezina Formation and possibly part of the Corumbatai Formation and appears to be restricted to the central part of the basin. It consists of mainly grey and reddish siltstones, shales and sandstones that were probably deposited in flood plain environments with locally developed lakes, not unlike environments present in the Lower Beaufort Group in the Karoo Basin to the east. A major unconformity separates the Rio da Rasto Formation from the overlying sandy Triassic sequences of the São Bento Group, which were deposited under more arid conditions (Bigarella and others, 1967; Fulfaro and Landim, 1976).

Along the active orogen explosive volcanism and predominantly felsic plutonism continued, especially in the Mitu Rift and in Patagonia. Continental depositional environments were dominated by red bed sedimentation, reflecting aridity, a feature that continued into the Triassic.

Arabia

Carbonate marine deposition continued in the Arabian region in a range of environments, although most of the central area was characterised by high-energy carbonate platform environments due to the shallow nature of the platform. Sabkha environments continued to deposit anhydrite and dolomitic limestones in the Arabian Gulf region; the anhydrite now acts as the seal for gas and condensate reservoirs within the Khuff Formation (Alsharhan & St. C. Kendall, 1986). Clastic material derived mainly from the western and southern hinterland, was deposited in non-marine and near-shore environments (Sharief, 1982). In Iran and southern Turkey, mixed clastic and clastic facies were deposited, including thin coal lenses, locally intercalated with reefal carbonates, on the margin of a basement high in southeast Turkey. Plant remains from the region are predominantly of Cathaysian affinity, however *Glossopteris* species are present within the assemblage, suggesting migration of Gondwanan elements to low latitudes during the latest Permian (Archangelsky & Wagner, 1983). Further west the marine influence of southern Tethys is evident in the Levantine Basin and in the Tunesia region where carbonate reefs flourished.

PERMIAN COAL IN GONDWANA

Coal deposition in Gondwana (Fig 9) occurred from Early to Late Permian and was generally restricted to a palaeolatitudinal belt ranging from approximately 45° S to 75° S. This zone represents the cold to cool temperate climatic zone where precipitation is high, and evaporation rates and temperatures are low, conditions ideal for peat swamp development. Generally, preservation of vegetation in the form of peat deposits results when precipitation exceeds 20mm per month for ten to twelve months of the year (Ziegler and others, 1987). The present day distribution of peat-forming environments is in both equatorial and in high latitude regions, equivalent to conditions in the Permian (Parrish & Barron, 1986). The Permian equivalent to the equatorial peat swamps are coal deposits in Cathaysia and probably the minor occurrences in northern Africa, Arabia and the Middle East.

The most prolific and widespread period of coal deposition was during the late Early Permian when coal swamps were present throughout the Gondwanan continent. Geological and faunal evidence indicates that most coal deposition during this period originated under cold to cool temperate conditions associated with the climatic amelioration following the extensive Late Palaeozoic glaciation. Gondwanan coal deposition during the Permian appears to have been diachronous; major coal deposition began throughout the supercontinent in the Early Permian but was restricted to eastern Gondwana by the Late Permian (Table 1). This was a response to the rotation of western Gondwana away from the south pole into more arid climate zones incompatible to coal accumulation, coupled with the development of increased monsoonal atmospheric circulation. The lowering of relative sea level from the Early to Late Permian and orographic barriers created by locally emerging highlands in many areas of the convergent orogenic margin have also influenced the distribution of coal measures.

Coal deposition in Gondwana occurred in a range of tectonic settings, from relatively stable cratonic platforms to grabens and foreland basins. Minor coal deposits are also preserved in the southern orogenic belt. The thickest coal seams, over 30 metres thick, are located within rift basins, for example the Raniganj Formation and Blair Athol Coal Measures. The Blair Athol coals probably represent raised bogs or mounded peat deposits (Smyth, 1980).

Figure 9. Coal distribution in Gondwana

STAGES	SOUTH AMERICA	AFRICA	ARABIA	INDIA	ANTARCTICA	AUSTRALIA
Late Late Permian		x	x	xxx	?xx	xxx
Early Late Permian	x	xx	x	x	xxx	xxx
Late Early Permian	xxx	xxx	x	xxx	xxx	xxx
Early Early Permian	xx	xx	x	xx	x	xx
Earliest Permian	x	x	x			

x minor   xx significant   xxx abundant

Table 1. Distribution of Coal Occurrences in Gondwana

The tectonic instability of Gondwana during the Permian led to the development of numerous rifts throughout the supercontinent, which aided in both the preservation of organic matter and maturation to form coal seams; coal rank has been shown to increase towards the centre of rift basins in southern Africa (Falcon, 1986). The stable cratonic platform basins (for example the Cooper, Paraná and Karoo Basins) contain laterally extensive but generally relatively thinner coal sequences. The Sydney-Gunnedah-Bowen basin system in eastern Australia contains thick, economic coal seams that accumulated in both extensional and compressive (foreland basin) regimes in the Early and Late Permian.

Permian coal in South America is mainly restricted to the Early Permian sequence in the intracratonic Paraná Basin; minor occurences are present along the orogenic western and southern margin. Studies on the floral composition of the coal seams in the Paraná Basin suggest that open-water moor facies, composed of detrital organic matter and algae associated with fine grained sediments, represents the dominant coal forming depositional environment (Marques-Toigo & Corrêa Da Silva, 1984; Corrêa Da Silva and others, 1984). The next most common coal depositional environment within the basin was limno-telmatic reed-moors, characterised by shrub-like plant communities. Forest (reed) environments are rarely represented and no examples of forest-terrestial moor environments, developed on raised soils adjacent to swamps, have been reported.

Coal deposits in southern Africa are located in cratonic margins or rifted, fault-bounded basins. The former is typified by the Karoo and Kalahari Basins, where coal deposition was strongly affected by palaeotopography, tectonics and palaeoclimate. The rift basins generally coincide with pre-existing structural weaknesses within the southern African craton. The rift basin coals such as in Zambia, Tanzania and Mozambique are generally hosted in thick sedimentary sequences, are areally restricted and contain variable coal seam distribution; the sequences are typically faulted.

Australian Permian coals occur throughout the continent and were deposited in a wide range of environments. Fluvial and fluvio-lacustrine systems were probably the most widespread coal-forming environments during the Permian, although delta-plain environments, during the mid to Late Permian (Sydney-Gunnedah-Bowen Basins) were the site of extensive peat swamps (Hobday, 1986; Brakel & Totterdell, 1988; in prep.). High relative sea level during the mid Permian probably increased humidity in the region. The generally cold to cool temperate and humid climate during the Permian was a major influence on peat accumulation and preservation, but its effect on coal types is difficult to quantify. Although recent studies on some inertinite-rich coals (Taylor and others, 1989), have suggested that freezing winter conditions during peat accumulation, may have caused dehydration (freeze drying) of plant material at the surface of the peat swamp, subsequent to coalification. Floral variation during the Permian appears to have had minor influences on the petrographic composition of the Permian coals in eastern Australia; tectonic control was the dominant factor (Hunt, 1989).

Permian coal deposition in peninsula India was largely controlled by fluctuating palaeoclimatic conditions and palaeodepositional factors. Climatic and associated floral variations from the Early to Late Permian are reflected in both the distribution, and to a certain degree, the type of coal (Navale & Saxena, 1989). Palaeotopography and tectonics were major controlling factors in coal deposition; coal swamps occurred within fluvial deposits that were generally aligned parallel to the major rifts. Changes in stream channel morphology during the Permian controlled the thickness, geometry and dimensions of of the coal seams (Casshyap & Tewari, 1984).

Minor fluvial to paralic coals were deposited in various localities on the southern margin of Tethys from North Africa in the west to Irian Jaya in the east. They are generally of little economic interest and are mainly thin, discontinuous and of poorer quality than coals in the main Permian Gondwanan basins. The maritime influence of Tethys probably increased humidity along the Gondwanan margin to create conditions locally suitable for peat accumulation.

CONCLUSIONS

Permian coals in Gondwana occur at a similar stratigraphic level thoughout the supercontinent ie. above the widespread Late Palaeozoic glacial deposits or equivalent strata, except in the northwestern region where climatic conditions were unsuitable for peat accumulation. The coal measures where generally deposited in humid cold to cool temperate climatic conditions following the amelioration of widespread glaciation.

Asselian sedimentation was dominated by dynamic and widespread continental and marine glaciation throughout Gondwana. A series of ice centres developed during the Late Carboniferous, often in regions of elevated terrain, and coalesced to form a major ice sheet or ice sheets. The time span of the Late Palaeozoic glaciation is uncertain, although there is evidence of glacial deposition from the Namurian to the Kungurian, with a maximum glacial advance during the Asselian. Thin carbonaceous beds and floral remains within the glacial sediments indicate that impoverished polar tundra vegetation was present in many regions of the supercontinent. Volcanism was active along the southern orogenic margin especially in the Australian region, where it was associated with both back-arc rifting and arc magmatism.

The Sakmarian saw a major retreat of glaciation, accompanied by a high stand of sea level, which resulted in the formation of extensive marine embayments throughout Gondwana. Post-glacial cool climates led to a change from tundra vegetation to swamps and Gangamopteris/Glossopteris forests. Low-sinuosity fluvial and lacustrine environments developed throughout Gondwana and peat began to accumulate in subsiding basins. Along the Tethyan margin, intermitent rifting, with local volcanism, was probably initiated and continued throughout the Permian.

The Artinskian-Kungunian, was characterised by widespread peat accumulation in palaeovalleys, lakes, deltas and coastal plains throughout Gondwana. These peat deposits, which were precursors to economic coal seams in South America, Africa, India and Australia, vary in quality, geometry and thickness, depending on palaeotopography and depositional environment. A transgressive event at the end of the Early Permian appears to have terminated major coal deposition in the Paraná, Karoo, Sydney and possibly the Bowen Basins. Tectonism in the southern orogen increased resulting in increased uplift and thrusting, whereas rifting continued along the northern Tethyan margin.

During the Late Permian (Kazanian-Ufimian) there was a resumption of coal deposition in deltaic environments in the Sydney Basin and marine inundation of the Bowen Basin. Shallow marine intertidal and lagoonal environments were present in the Paraná Basin, whereas in the Karoo Basin turbiditic sediments, derived from the uplifted Cape Fold Belt, were deposited in a deep water trough in the southern part of the basin. Coal beds continued to accumulate in rift and intracratonic basins in southern Africa, but coal deposition had ceased in South America and temporarily ceased in India.

Relative sea-level was at its lowest level during the Tatarian-Dorashamian and coal deposition was generally restricted to eastern Gondwana, i.e. the Antarctic, Indian and Australian regions, where thick coal sequences developed in fluvial and deltaic environments. These coals are preserved in foreland, cratonic and rift basins. In southern Africa and South America fluvial to fluvio-lacustrine sediments continued to be deposited, although locally, playa-flood plain environments began to develop as aridity increased in the region, a process that continued into the Triassic.

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APPENDIX 1

MAIN INFORMATION SOURCES

Gondwana:
Hambray & Harland (1981)

Antarctica:
Barrett (1991) - Antarctica
Coates (1972) - Antarctica
Barrett et al. (1986) - Beardmore area
Williams (1969) - Pensacola Mountains
Elliot (1975) - Antarctica
Smellie (1987) - Antarctic Peninsula
Smellie (1981) - West Antarctica
Collinson et al. (1986) - Victoria Land
McKelvey et al. (1972) - Victoria Land
Rose & McElroy (1987) - Darwin Mountains
Barret & Kohn (1975) - Victoria Land
McKelvey & Stephenson, 1990 - Prince Charles Mountains
Webb & Fielding (1991) - Prince Charles Mountains
Mond (1972) - Prince Charles Mountains
Dalziel (1984) - Antarctic Peninsula
Gee (1989) - Antarctic Peninsula
Storey et al. (1987, 1988) - Antarctic Peninsula
Hyden & Tanner (1981) - Antarctic Peninsula:
Aitchison et al. (1988) - Ohio Range

Arabia Region:
Kruck & Thiele (1982) - Yemen
Alsharhan & Kendall - Persian Gulf
Qidwai et al (1988) - Oman
Levell et al (1988) - Oman
Glennie et al (1974) - Oman
Robertson & Searle (1990) - Oman
Blendinger et al. (1990) - Oman
McClure et al (1988) - Arabia
Al-Laboun (1988) - Arabia
Buday (1980) - Iraq
Weissbrod (1976) - Near East
Ala & Moss (1979) - Turkey & Syria
McBride et al. (1990) - Syria
Temple & Perry (1962) - Turkey
Eshet (1983) - Israel
de la Grandville (1982) - Oman
Bege (1986) - Arabia
Saint-Marc (1979) - Arabian Peninsula
Szabo & Kheradpir (1978) - Iran
Blendinger (1988) - Oman
Lippard et al. (1988) - Oman
Hudson & Sudbury (1959) - Oman & Arabia
Atliner (1983) - Turkey
McClue et al. (1988) - Arabia

India Region:
Cassyap & Srivastava (1987) - India
Robinson, 1967 - India
Ahmed et al (1985) - Pakistan
Friedrich & Meng Sze Wu (1987) - India
Rao et al (1979) - Rajastan
Venkatachala & Tiwari (1987) - Sth India
Tripathi & Singh (1985) - Northwest Himalayas
Srikantia (1985) - Himalaya
Cooper (1983) - Arckaringa Basin
Sakai (1983) - Central Nepal
Acharyya (1975) - Sikkim
Casshyap & Qidwai (1974) - Pench Basin
Mitre (1987) - Assam
Banerjee (1987) - Godvari Basin
Casshyap & Tewari (1984) - India peninsula
Pareek (1981) - Rajastan
Khan (1987) - Rajmahal Basin
Ramanamurthy (1985) - Godvari Basin
Rai & Shukla (1977) - Satpura Basin
Rao (1987) - Damodar Basin
Pakistani - Japanese Group (1985) - Pakistan
Shukla & Rai (1977) - Satpura Basin
Casshyap (1980) - Mahuda Basin
Kapoor & Singh (1987) - Himalayas
Srivastava et al. (1987) - Eastern Himalayas
Tripathi & Roy Chowdhury (1981) - Eastern Himalayas
Tripathi & Singh (1987) - Himalayas
Reuber et al. (1987) - Himalayas
Kapoor & Tokuoka (1985) - Nepal
Ghosh (1983) - Darjeeling
Banerjee & Das Gupta (1981) - Bhutan
Mukhergee et al. (1988) - Bhutan
Gaetani et al. (1990) - Karakoram
Gergan & Pant (1983) - Karakoram
Wang et al. (1981) - Tibet
Wei & Tan (1983) - Tibet
Liang et al. (1983) - Karakoram
Wang (1985) - Tibet
Chang, Pan & Sun (1984) - Tibet,
Yang et al (1986) - Tibet
Liu (1989) - Tibet
Nie et al. (1983) - Tibet

Australian Region
Brakel & Totterdell (in prep) - Australia
Veevers (1984) - Australia
O'Brien (1986) - Murray Basin
Brown & Stephenson (1991) - Murray Basin
Herbert & Helby (1980) - Sydney Basin

Australian Region cont.
Flood & Runegar (1982) - New England Orogen
Kleeman (1988) - New England Orogen
Harrington (1983) - Gympie Terrane
Day et al (1983) - Queensland
Brakel (1989) - Bowen Basin
O'Brien (1987) - Bowen Basin
Dickens & Malone (1973) - Bowen Basin
Fielding et al. (1991) - Bowen Basin
Evans (1980) - Gallilee Basin
Wells (1989a) - Gallilee Basin
Smart & Radasi (1979) - Laura Basin
Playford et al (1976) - Perth Basin
Backhouse (1990, 1991) - Collie Basin
Bird (1985) - Timor
Jackson & Van de Graff (1981) - Officer Basin
Forman et al (1981) - Canning Basin offshore
Towner & Gibson (1983) - Canning Basin
Yates et al (1984) - Canning Basin
Veevers & Roberts (1962) - Bonaparte Basin
Hocking et al (1988) - Carnarvon Basin
Allen et al (1978) - Browse Basin
Harris & Ludbrook (1966) - Mallabie Trough
Cooper et al (1982) - Polda Trough
Alley & Bourman (1984) - Troubridge Basin
Foster (1974) - Troubridge Basin
Townsend (1976) - Arckaringa Basin
Burret & Martin (1989) - Tasmanian Basin
Banks & Clarke (1987) - Tasmania Basin
Morey (1988) - Bonaparte Basin offshore
Thorton (1979) - Cooper Basin
Wells & O'Brien (1989) - Cooper Basin
Douglas & Ferguson (1988) - Western Victoria
Coalfield Geology of NSW (1978) - Oaklands Basin
Youngs (1975) - Perdika Basin
Bird (1987) - Timor
Dow et al. (1988) - Irian Jaya
Bradshaw et al. (1990) - Arufura Basin
Korsch & Wellman (1988) - New Zealand
Suggate (1978) - New Zealand
Bradshaw et al. (1980) - New Zealand
Crook & Freary (1982) - New Zealand
Spoli & Gregory (1980) - New Zealand

South America
Gonzalez de Juana et al (1980) Venezuela
Helwig (1972) - Boliva
Shagam (1975) - Columbia
Aguirre (1985) - Chile
Ulina & Biddle (1987) - Patagonia
Soares et al. (1973) - Parana Basin
Soares & Cava (1982) - Parana Basin
Zalan et al. (1987) - Parana Basin
Franca & Potter (1991) - Parana Basin
Bigarella et al. (1967) - Parana Basin
Fulfaro & Landim (1976) - Parana Basin
Correa da Silva et al. (1984) - Parana Basin
Marques-Toiga & Correa da Silva (1984) - Parana Basin
Machado (1973) - Parana Basin
Oelofsen (1987) - Parana and Karoo Basin
Mabesoone (1977) - Parnaiba Basin
Schobbenhaus et al. (1984) - Brazil
Eckel (1959) - Paraguay
Mones & Figueiras (1980) - Uruguay
Lima & Sundaram (1982) - Brazil
Friederich (1987) - Argentina
Andreis & Cuneo (1989) - Patagonia
De Giusto et al. (1980) - Patagonia
Ramos (1989) - Magallanes Basin
Ramos (1988a,b) - Andean region
Mojica & Dorado (1987) - Columbia
Sanchez (1984) - Venezuela
Arnold (1966) - Venezuela
Forsythe (1982) - Southern S. America
Chamot (1965) - Bolivia
Flores-Williams (1978) - Bolivia
Amos (1981) - Argentina
Miller (1962) - Venezuela
Newell et al. (1953) - Peru
Bahlburg et al. (1987) - Chile
Pitcher et al. (1985) - Peru
Herve et al. (1987) - Andes Mountains
Breitkreuz et al. (1989) - Andes Mountains
Miller (1984) - Andes Mountains
Mpodozis & Ramos (1990) - Andes Mountains
Kay et al. (1989) - Southeren S.America
Rapela & Kay (1988) Andes Mountains
Linares et al. (1988) - Argentina
Sad et al. (1982) - Amazon Basin
Mosmann et al. (1984) - Amazon Basin
Szatmari et al. (1979) - Amazon Basin
Bar & Reigal (1980) - Ghana & Brazil
Azcuy (1985) - Argentina
Russo et al. (1980) - Chaco-Parana Basin
Padula & Mingramm (1969) - Chaco-Parana Basin
Limarino & Spalletti (1986) - Paganzo Basin
Archangelsky & Azcuy (1985) - Argentina
Rocha-Campos & Archangelsky (1985) - South America
Cobbing (1985) - Peru
Wilson (1990) - Bolivia
Dalmayrac et al. (1980) - Andes Mountains
Lopez Gamundi (1988) - South America
Andreis et al (1987a) - Argentina
Andreis et al (1987b) - Tepeul Genoa Basin
Azcuy et al. (1987a) - San Rafael Basin
Azcuy et al. (1987b) - Paganzo Basin

Africa

Rust (1975) - Southern Africa
Oesterlen (1976) - Angola
Stratten (1986) - Karoo Basin
Truswell & Ryan (1969) - Karoo Basin
Davies (1961) - Swaziland
De Jager (1961) - Karoo Basin
Ortlepp (1986) - Limpopo Basin
Smith (1984) - Botswana
Clark et al. (1986) - Botswana
Kingsley (1985) - Namibia
March & McDaid (1986) - Namibia
Stavrakis (1985) - Namibia
Schreuder & Genis (1975) - Namibia
Duguid (1986) - Zimbabwe
Tavener-Smith (1956) - Zambia
Gair (1959) - Zambia
Zambia Ministry of Mines (1983) - Zambia
Gair (1960) - Zambia
Utting (1976) - Zambia
Utting (1978) - Zambia
Money & Drysdall (1975) - Zambia
Veatch (1935) - Zaire
Rocha-Campos & Bernades de Oliveira (1972) - Angola
Kogbe & Burollet (1990) - Africa
Lefranc & Guiraud (1990) Northern Africa
Neto (1976) - Mozambique
Verniers (1989) - Mozambique
Cadle et al (1990) - Karoo Basin
Smith (1990) - Karoo Basin
Stravrakis (1986) - Karoo Basin
Cairncross & Cadle (1987) - Karoo Basin
Greenshields (1986) - Karoo Basin
Winter et al. (1987) - Karoo Basin
Cairncross (1987, 1989) - Karoo Basin
Le Blanc Smith (1980) - Karoo Basin
McLachlan & Jonker (1990) - Karoo Basin
Bell & Spur (1986) - Karoo Basin
Roberts (1988) - Karoo Basin
Holland et al. (1989) - Karoo Basin
Cairncross & Winter (1984) - Karoo Basin
Hobday (1986) - Australia & S. Africa
S. African Committee for Stratigraphy (1980) - Karoo Basin
Tankard et al. (1982) - South Africa
Visser (1983a, 1987, 1989) - Southern Africa
Visser (1983b) - Botswana
Lister (1987) - Zimbabwe
Memmi et al. (1986) - Tunesia
Doubinger & Fabre (1983) - Becher Basin
El Wartiti et al. (1990) - Morocco
Van Houten (1976) - Morocco
Busson & Burollet (1973) - Tunesia
Klitch (1987) - N.E. Africa
Diaz (1985) - North Africa
Fabre (1985) - Niger
Soliman & El Fetouh (1970) - Egypt
Crow (1952) - Ghana
Klitzsch (1972) - Murzuq Basin
Radeilli (1975) - Malagasy
Boast & Nairn (1982) - Malagasy
Coffin & Rabiowitz (1988) - Malagasy
Davidson & McGregor (1976) - Ethiopia
Kreuser (1987) - Tanzania
Assefa (1988) - Ethiopia
Saka & Miyata (1979) - Kenya
Kenya Ministry of Energy (1984) - Kenya
Cahen (1954) - Zaire
Macrae (1988) - Northern S. Africa
Dow et al. (1971) - Ethiopia
Kamen-Kaye & Barnes (1979) - Somalia, Kenya
Mbede (1987) - Kenya
Stuart et al. (1977) - Kenya
El-Arnauti & Shelmani (1985) - Libya
Bigotte & Obellianne (1968) - Niger
Fabre (1970) - Mali
Salem & Busrewil (1980) - Murzuq Basin
Klitzch (1986, 1987) - Sudan & Egypt
Klitch & Squyres, (1990) - Sudan & Egypt
Said (1962) - Egypt
Afonso (1984) - Mozambique
Falcon (1984) - Mozambique
Micholet et al. (1970) - Gabon
Chamber of Mines (undated) - Malawi
Wopfner & Kreuser (1986) - Tanzania
Wopfner & Kaaya (1991) - Tanzania
Harkin (1952) - Tanzania
Saka & Yairi (1977) - Malawi
Scogings & Lenz (1961) - Swaziland
Kreuser et al. (1988, 1990) - Tanzania
Yemane et al. (1989) - Malawi
Yemane & Kelts (1990) - Southern Africa
Hankel (1987) - Tanzania
Jalfin & Bellosi (1983) - Falkland Islands
Greenway (1972) - Falkland Islands

PLATE 1. PERMIAN STRUCTURAL MAP OF GONDWANA

BHP-Utah Minerals International Inc. 1991

LATEST CARBONIFEROUS - EARLIEST PERMIAN
(STEPHANIAN - ASSELIAN)

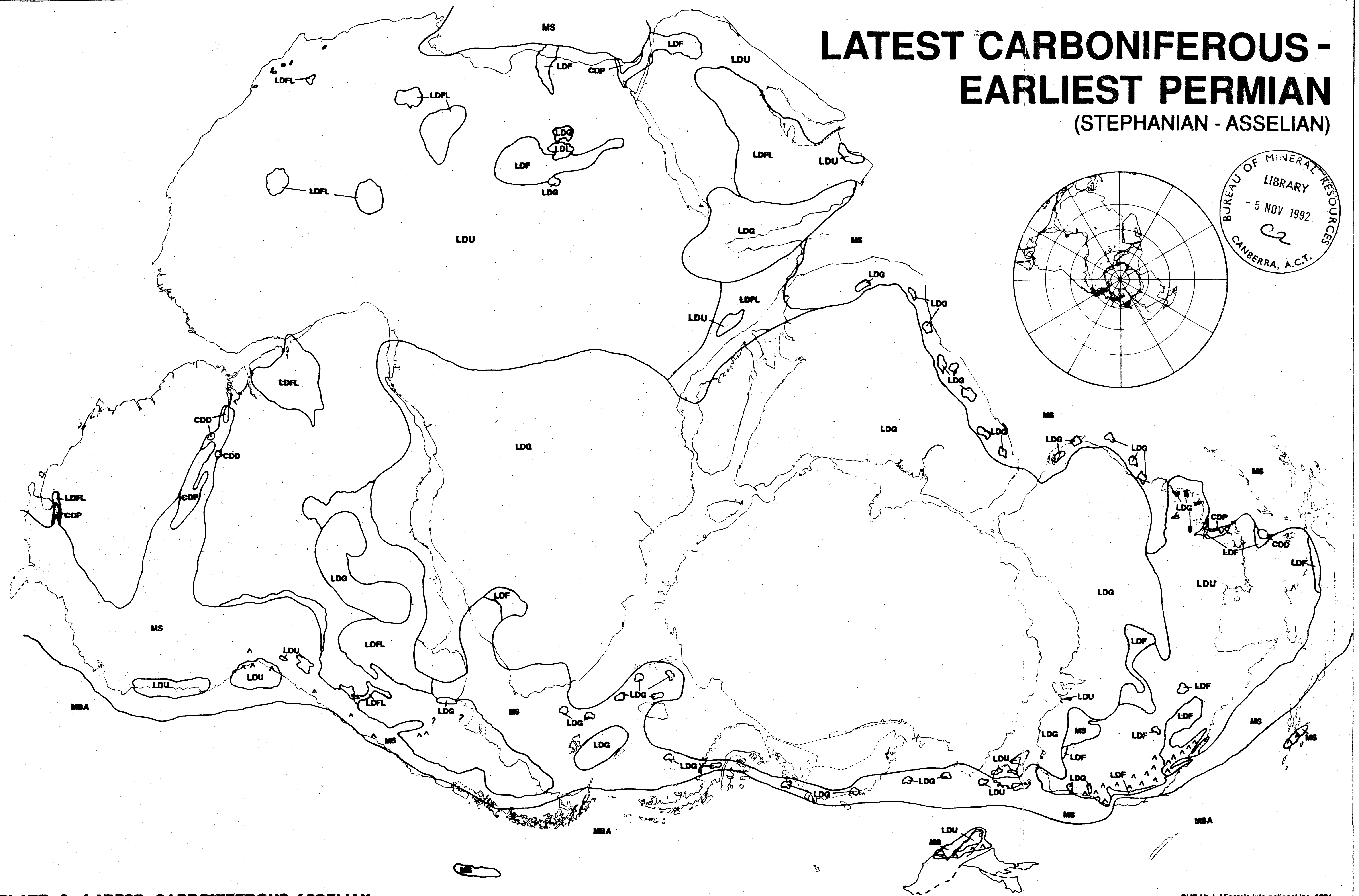

PLATE 2. LATEST CARBONIFEROUS-ASSELIAN

BHP-Utah Minerals International Inc. 1991

EARLY EARLY PERMIAN
(SAKMARIAN)

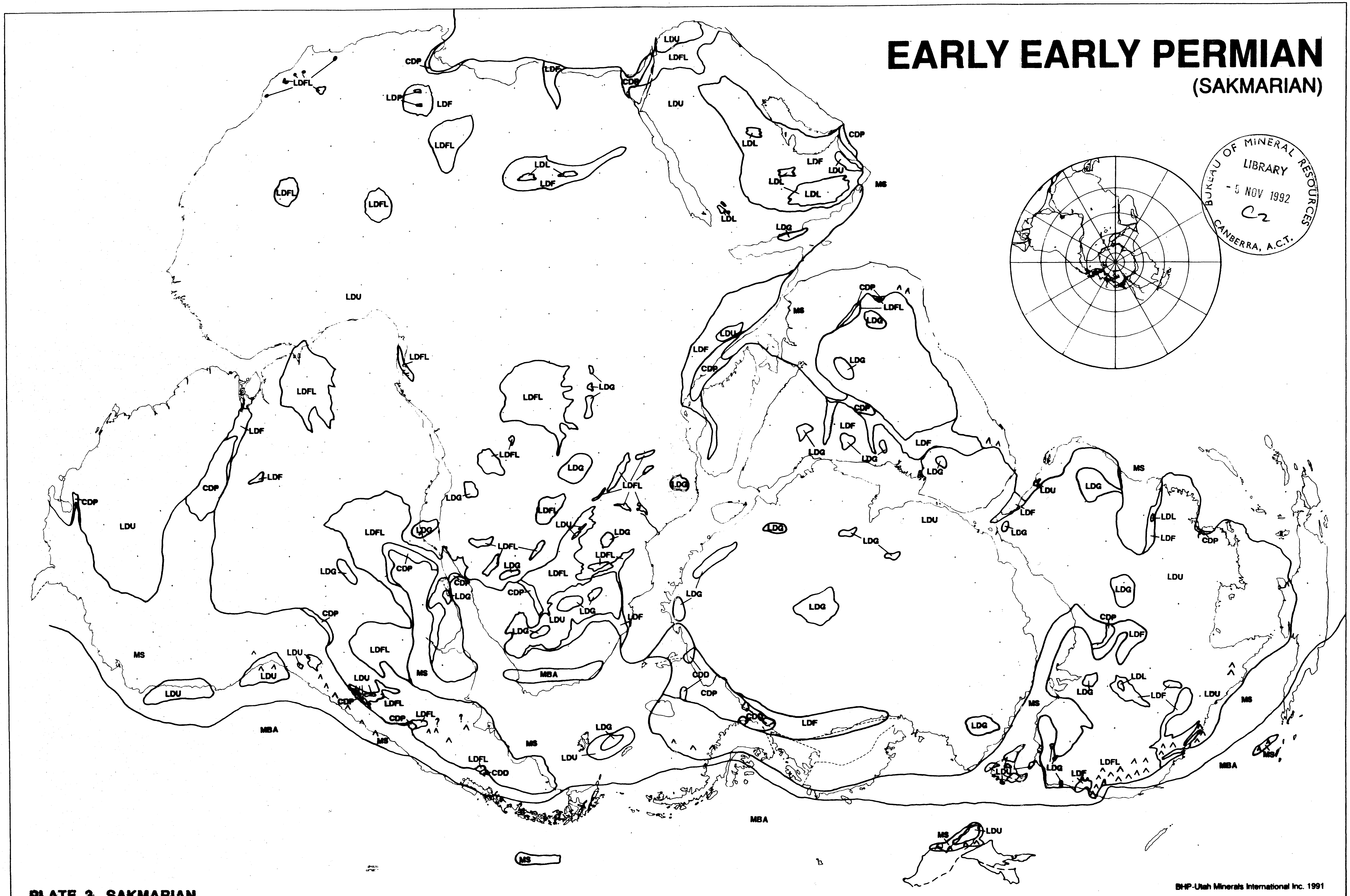

PLATE 3. SAKMARIAN

BHP-Utah Minerals International Inc. 1991

LATE EARLY PERMIAN

(ARTINSKIAN - KUNGURIAN)

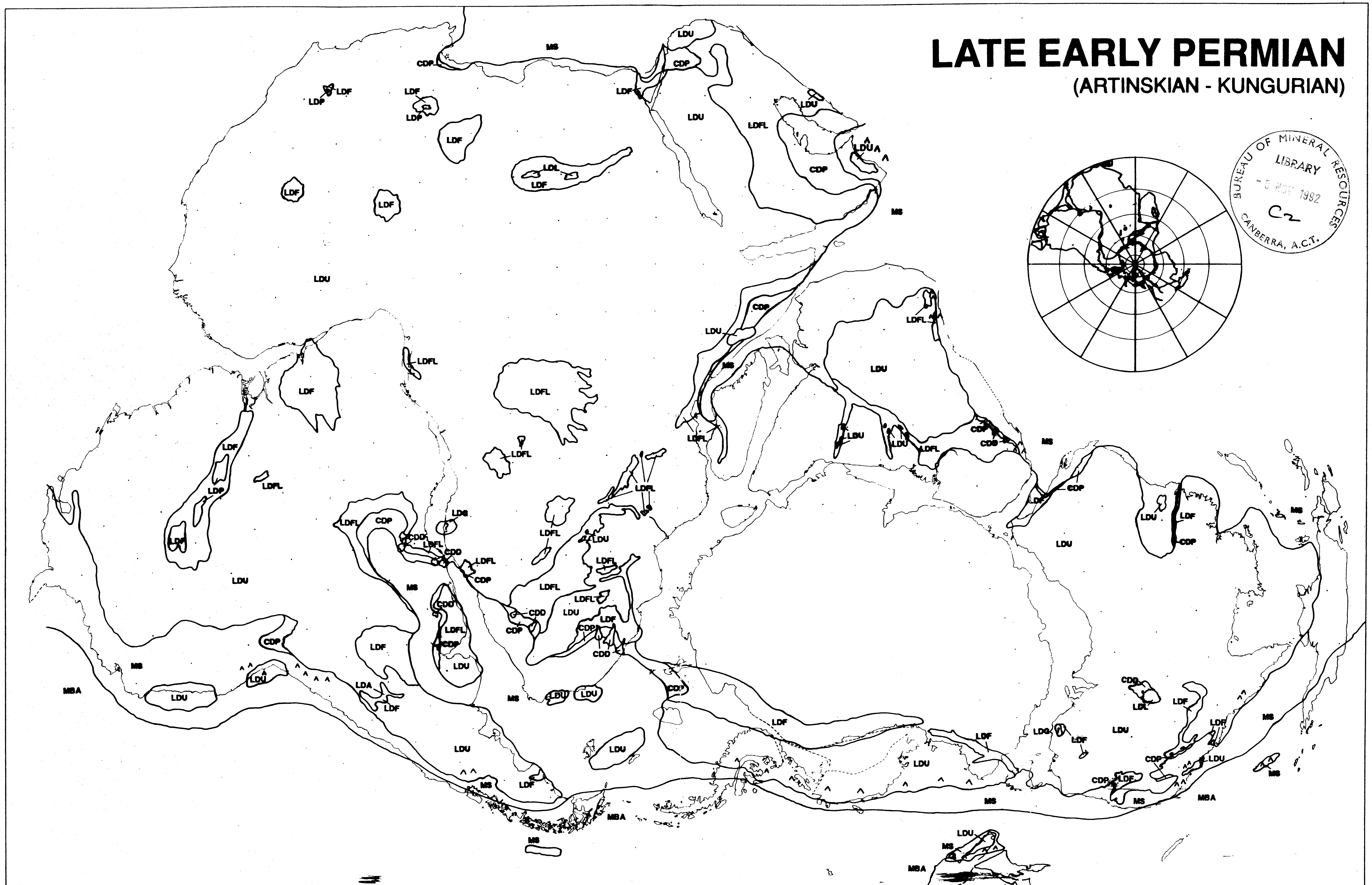

PLATE 4. ARTINKSIAN - KUNGURIAN

BHP-Utah Minerals International Inc. 1991

EARLY LATE PERMIAN

(UFIMIAN - KAZANIAN)

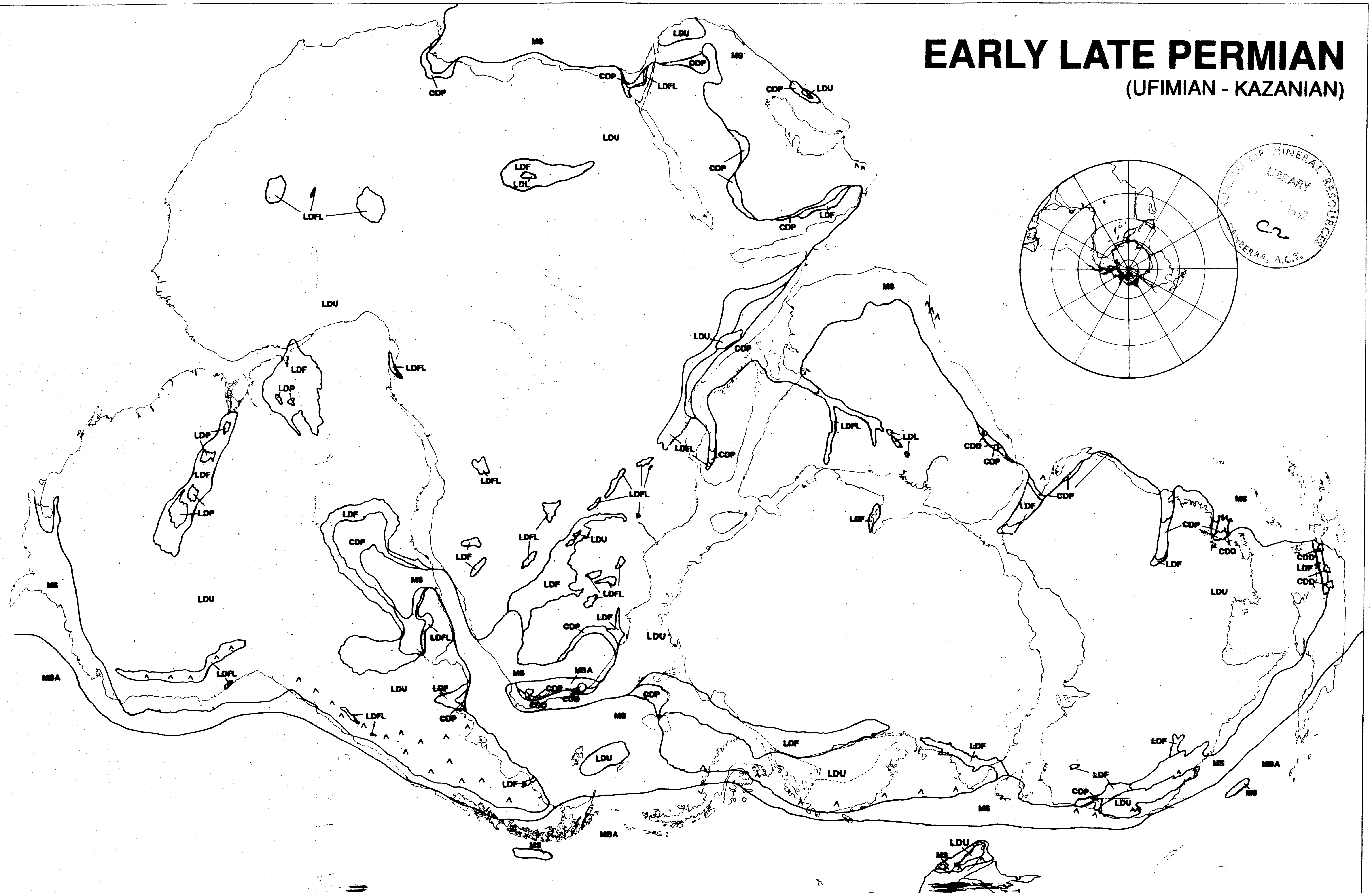

PLATE 5. UFIMAN - KAZANIAN

BHP-Utah Minerals International Inc. 1991

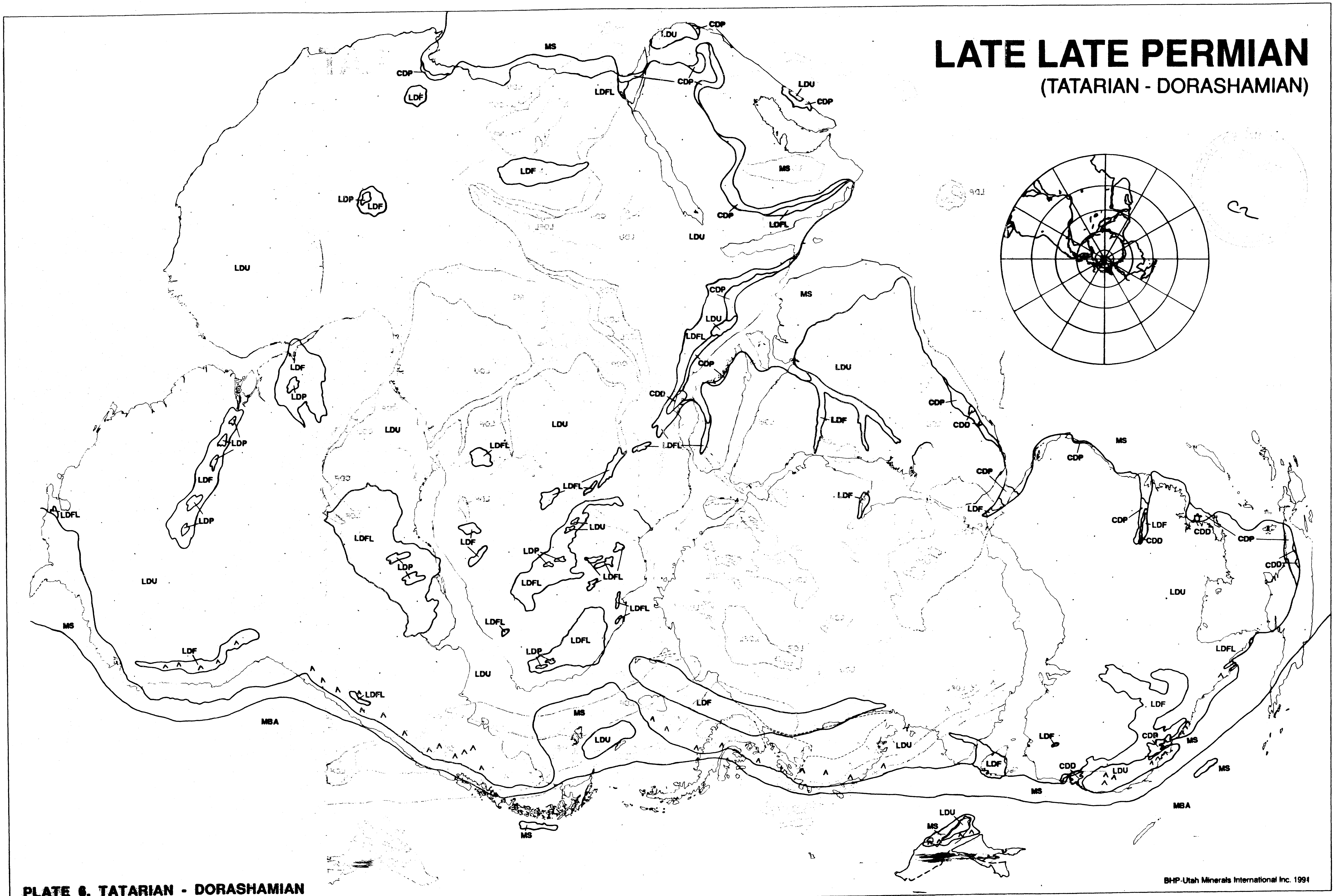

PLATE 6. TATARIAN - DORASHAMIAN