1 Major global change: framework for the modern world

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In so many features the Permian and Triassic periods differed from the present that if we could be transported back to that distant past, surely we would think that we were on another planet. The plants and animals would be largely unrecognized – no mammals, and none of our modern trees or grasses. Although the nature and dispositions of the seas, lands, and mountains during that time are subject to different interpretations and conflicting views, who can doubt that the world’s geography would be unrecognizable? The climate would have varied widely, from very cold at the beginning of the Permian (perhaps not unlike the glacial climate of the world a few thousand years ago) to a hot, dry climate during the Triassic, like nothing we see at present, followed by a warm climate continuing into the Jurassic.

Major changes in faunas were associated with the beginning of the Jurassic period, as reviewed by Boucot (1990), Dickins (1993a), and Hallam (1981). Boucot stated that “the modern marine ... benthiic fauna and communities really begin with the Jurassic.” In the latter part of the Permian and during the Triassic the earth was wracked by vast earthquakes, and great mountain chains were formed. There was magmatic-volcanic activity on an enormous scale. Some of those events are described in this volume, and some of the most interesting problems for future investigation are considered.

Carboniferous and Lower Permian

Neither the Carboniferous events associated with the Hercynian Orogeny (or Hercynian orogenic phase) nor the major regressions and progressive continentality shown by the Upper Carboniferous sequences (the Hercynian Gap) are covered in this volume, except in the area of South America, where López-Gamundi and Breitkreuz, in Chapter 2, describe the widespread hiatus between the Upper Devonian and the Carboniferous strata. Their information supplements prior studies of the changes associated with the massive adaptive radiation of faunas at the beginning of the Carboniferous (Boucot, 1990).

The events marking the end of the Carboniferous and the beginning of the Permian have already been described (Dickins, 1988, 1989, 1991, 1992a,b). An extensional episode has been reported by Visscher (1993) for southern Africa and by Yang, Liang, and Nie (1993) for Tibet and western China. Now, in Chapter 2, a significant episode of extension and accompanying basaltic-volcanic activity is described by López-Gamundi and Breitkreuz for southern South America. Parallel events, with tectonic faulting and basaltic volcanism, seem to have occurred in the western and northern parts of North America (Beauchamp, Harrison, and Henderson, 1989; Miller and Harewood, 1990). Lower Permian rocks in Mexico, mostly of a platform type, are described in Chapter 3, by González-León, Lucas, and Roldán-Quintana, and are distinguished from Upper Permian and Upper Triassic deposits in an area where thrusting has been shown to have occurred from the mid-Permian to the middle Triassic. In this volume it is the mid-Permian events and those of later times that are especially well described.

Mid-Permian (Kungurian–Ufimian)

“Mid-Permian” is used herein to refer to the sequences associated with the boundary between the Kungurian and the Ufimian stages of the twofold Russian subdivisions of the Permian. Traditionally the Kungurian is placed in the Lower Permian, and the Ufimian in the Upper Permian. Some possible modifications of that placement are discussed later in relation to Kotlyar’s Chapter 4 in this volume.

In Chapter 5, Cassinis, Perotti, and Venturini describe the tectonic and sedimentary events during the mid-Permian in the European Southern Alps. They present a mechanism for the development of extensional (pull-apart) basins that they ascribe to a transcurrent regime associated with the late Hercynian interval. However that interval may be named, certainly in the European Southern Alps it represents a remarkable tectonic episode (or perhaps episodes) in which the early Permian marine basins were entirely eliminated and massive uplifts resulted in widespread unconformities, with the subsequent sedimentation beginning with thick conglomerates lying on well-developed weathering profiles (Cassinis, 1988; Italian IGC-203 group, 1988). They believe that that tectonic activity had long-lasting effects and subsequently influenced Alpine orogenic development. In Chapter 6, Comi and co-workers examine the tetrapod footprints and palynology of that interval and the overlying
sequences up to the end of the Permian. They draw important conclusions about the correlations for those sequences based on combined studies of tetrapod footprints and the palynology in the European Southern Alps. Their work indicates that the sequences are quite complicated, reflecting large-scale movements not only in the mid-Permian but also in later Permian times, perhaps especially associated with the Dzhulfian and Zachstein stages. Their work raises further questions about many of the traditional terms and concepts associated with the nonmarine geology of western Europe.

Kothyar’s correlation in Chapter 4 offers the possibility of a better understanding of those events. She refers to the two parts of the Uliamian type area and associates the lower part (the Solikamsk) with the underlying Lower Permian, and the upper part (the Sheshminsky) with the overlying beds, and she correlates that with the Roadian Stage. This calls for some reconsideration of the boundary between the Lower and Upper Permian in the Russian type area, currently placed at the base of the Uliamian. Detailed field data will be needed to elucidate the character of the Uliamian and its biota in the type area. In Australia, Daubich nites occurs with a Kangarian-type ammonoid and other pre–Upper Permian elements (Dickins et al., 1989), and therefore it cannot be taken as defining the base of the Upper Permian if that base is to be regarded as post-Kungurian.

Yang and co-workers (Chapter 7) outline those events in China, and Dickins and Phan (Chapter 8) discuss the same material in regard to Vietnam. Yang and co-workers redefine the Chishia beds and the units on either side, and now further field work seems desirable to clarify those relationships and to describe the faunas, especially the various species of Misellina and their ranges. According to Leven (1993), there are unconformities in South China for that interval, and more information on those, together with data on the faunal relationships and the tectonic movements, will be illuminating. Leven’s work indicates that there seems to be considerable confusion at present regarding recognition of species such as Misellina claudiae and regarding the definition of the base of the Chishia (Yang, Chen, and Wang, 1986). The type areas for the Chishian Stage and the Maokouan Stage are separated by a considerable distance, and that may be a hindrance to an understanding of their relationship. This work is particularly important for the implications it may have for the International Standard Stratigraphical Scale. As in Japan, important movements appear to have been likely at that time in Vietnam, and detailed studies of the fusulinid faunas should throw light on this matter. Thus far, good examples of conodont faunas have not been found in those sequences in Vietnam.

In the Russian Far East, important changes occurred in the mid-Permian, including major changes in the types and distributions of basins, and there were distinctive patterns of magmatic and volcanic activity. Those are dealt with in the chapters by Zimin (Chapter 9, on land plants) and Vrzhenkov (Chapter 10, on volcanism). Those changes paralleled the changes in many other parts of the world, as, for example, in South America (López-Gamundi and Breitkreuz, Chapter 2) and in Vietnam (Dickins and Phan, Chapter 8). Chapter 11, by Khetchikov and co-workers, is particularly interesting, indicating the mineralization patterns associated with various parts of the Permian and Triassic. Mineralization seems to have been periodic, but its relationships to the various events studied in this project are poorly known. Gold mineralization seems to have been very common during the middle-late Permian and is known, for example, from eastern Australia (Olgers, Flood, and Robertson, 1974; Bottome, 1986) and was studied at our field visit to western North America (Vallier, 1992). Epithermal gold, accompanied especially by silver, is also a feature of these sequences in Vietnam (J. M. Dickins, personal observation), in Primorye (Khetchikov et al., Chapter 11, this volume), and in southern South America (Delpino et al., 1993).

Chapter 12, by Dickins, reviews the mid-Permian interval for selected areas around the world, detailing the various names for the orogenic activities and the surprisingly coeval character of the movements. It describes the widespread reflection observed in the upper part of the Lower Permian and the tectonic movements and foldings associated with intrusive and explosive volcanic activity, transgressive unconformity, and basin reconstruction whose beginnings are reflected in the Upper Permian. Chapter 12 also discusses the faunal changes, ascribing them to the environmental changes. In eastern Australia, the name Hunter-Bowen has been applied to the orogenic activity beginning in the late Permian and extending into the Triassic. It has been argued elsewhere (Dickins, 1987) that such activity continued to the end of the Triassic and that the name can usefully be combined with the Indosinian, as Hunter-Bowen (Indosinian), to indicate an orogenic cycle between the Hercynian and the Alpine-Himalayan cycles. The name Indosinian has been used in southern and eastern Asia generally for movements that took place during the late Permian and Triassic or parts thereof. In Chapter 8, Dickins and Phan attempt a description of the Indosinian Orogeny in Indochina, from where the name is derived. Elsewhere in this volume, the names “late Hercynian” and “Hercynian” are used for the Permian orogenic movement, and this is a matter on which we might reach consensus through discussion.

Upper Permian

A major success of IGCP Project 272 has been to recognize the outstanding features associated with the Midian–Dzhulfian boundary. This important event has long been recognized in Japan as marking the boundary between the Middle and Upper Permian in the Japanese traditional scale. In China it marks the boundary between the Yangshinian (Yangzijnian) and Lopingian series, generally, in the past, referred to as the Lower and Upper Permian. That time was marked by an outpouring of a “flood basalt,” the Emchishan Basalt. Elsewhere in the Tethyan region that corresponds to the Midian–Dzhulfian boundary (Kotlyar, Chapter 4, this volume), frequently considered as the upper boundary of the Middle Permian in a threefold Permian subdivision. The significance of that event was recognized by
Dickins (1991) from his work in Japan and was reported at the IGCP-272 meeting in Sendai. That strong tectonic activity is reflected in the separation of the Kanonkura and Toyama series (Middle and Upper Permian, as traditionally used in Japan). At that time, carbonate platforms, some of which had existed since the Carboniferous, were broken up and deluged with largely siliceous volcanic and volcanic-lithic material (Sano and Kanmura, 1991), and deep crustal fracturing led to large-scale basic magmatic and volcanic activity, associated with periods of intermediate and acidic magmatism (‘ophiolites’). At the Sendai meeting, Phan (1991a) also reported on an unconformity at that level in Vietnam.

Subsequently, coeval changes were recognized in China (Yang et al., 1993), and extensive faunal changes were tabulated by Jin (1993). Further information was provided by Phan (1993), from Vietnam, where the unconformity at that level was accompanied by basaltic formation, strong magmatic and volcanic activity featuring a wide range of compositions, and apparently important mineralization. Dickins and Phan (Chapter 8, this volume) describe that episode further in Vietnam and its relationship to the Indonesian. No doubt that phase of the earth’s development will eventually be recognized in other parts of the world, and perhaps it may explain some of the puzzling features associated with the Zechstein Stage. Yang et al. (Chapter 7, this volume) suggest recognition of a stage in China at that level. They ascribe the tectonic activity to the Dongwu movement. Some problems remain concerning the ranges and definitions at that level, especially in regard to the Lepidololina kumaensis fauna. In Japan, L. kumaensis appears to have been confined to the Toyoma (Dickins, 1991), but elsewhere it has been reported from an earlier time (Kotlyar, Chapter 4, this volume). That needs confirmation, and possibly the missing section now being studied in China may help in the solution of this problem.

Permain–Triassic boundary sequences and events

The information presented in these chapters adds to the detailed account given in a previous volume reporting on IGCP-203 (Sweet et al., 1992) and the further accounts provided by Zishun Li et al. (1991) on South China and by Kamada (1991) on Japan. Erwin (1994) has recently reviewed “the Permo-Triassic extinctions” and has drawn similar conclusions. Wignall and Hallam (1993) have emphasized the effects of anoxia, but their conclusions about the importance of a single factor remain to be substantiated.

Yang et al. (Chapter 7, this volume) emphasize the natural causes of the extinctions, namely the widespread regression and the volcanic activity. Ezaki (Chapter 13, this volume) traces the extinction events in the corals and concludes that the changes in the biota were not confined to a single, short-lived crisis, but represented changes over a long period of time during the Permian, culminating at the boundary. Already before the end of the Permian, restriction of carbonate platforms had adversely affected the colonial wagenoplanellids, and the last rugose corals did not survive the Changhsingian. Chapter 14, by Ezaki and Kuwahara, details the changes in the cherts of Japan and the radiolarians they contain. Particularly interesting is the absence, thus far, of the Griesbachian and Dienerian in the lower part of the Lower Triassic. This is consistent with the absence of marine deposits elsewhere in Japan in the lower part of the Triassic (e.g., Kamada, 1991). Kamada (1991) reported the unconformable relations of the Permian and Lower Triassic in northeastern Honshu (Japan) and a series of pebbles in the Triassic, not only from the west but also from the east. The search for an explanation for that raises some interesting possibilities. For example, were there very large scale changes in sea-floor levels?

The late Changhsingian (Changxingian) ammonoids, bivalves, and brachiopods from South Primorye (Russian Far East), discussed by Zakharov, Oleinikov, and Kotlyar in Chapter 15, record a very late part of the Permian in that region. However, an important structural change and general hiatus can be shown above the Permian, as in all of Japan, and extensive volcanic activity (as in the Chinese region) is reflected in the latest part of the Permian, associated with the boundary. In Chapter 16, Rudenko, Panasenko, and Rybalka report very late Permian radiolarians and conodonts from Primorye (Sikhote-Alin). Oleinikov radiolarians are well known, but they also record probable Indian radiolarians, which confirms distinctive changes from the Permian radiolarians to the Triassic radiolarians.

It has recently been suggested that the eruption of the Siberian traps either caused or had a strong effect on the Permian–Triassic extinctions (e.g., Haski and Farrar, 1991; Renne and Basu, 1991; Campbell et al., 1992; Erwin, 1994). Some sweeping claims regarding the accuracy of the dating and the geologic context of the traps have not been helpful in clarifying this problem. The radiometric dating is not sufficiently accurate, and the geology of the traps not well enough known, to allow a firm conclusion. Even if those eruptions did not coincide with the boundary, it is clear enough that they were associated with a time of very strong volcanic and tectonic activities. Large-scale eruptions at the boundary would not explain the changes that were already going on during the Permian.

Lower Triassic

Although it is fairly easy to distinguish the Upper Triassic from the Middle Triassic on the basis of its geologic nature and geographic distribution, at present it is not so easy to distinguish between the Middle Triassic and the Lower Triassic. A distinctive regressive-transgressive phase has been described for the Arctic region by Embry (1988) and Moerk (1994), and we have observed the marked hiatus at the base of the Anisian in the Southern Alps of Italy. There is sufficient evidence of a major change associated with the Lower–Middle Triassic boundary for the two units to be considered separately in this review. The widespread, large-scale volcanic and magmatic activities of the Upper Permian, with a large acidic component (Dickins, 1992b), continued into the Triassic. In Chapter 17, Sakhae identifies two major phases of basic-trap formation: in the Lower Triassic and in the Upper Triassic–Lower Jurassic.
Khetchikov et al. (Chapter 11, this volume) report epigenetic mineralization associated with the volcanic and intrusive activities, not only during the Upper Permian but also during the Lower Triassic and throughout the rest of the Triassic. They report alluvial gold in the basol conglomerates of the Lower Triassic, which rest unconformably on older rocks, similar to occurrences in Vietnam. Dickins and Phan (Chapter 8, this volume) report continued igneous activity during the Lower Triassic. In the Songda Depression, basic activity was important, a feature of that structure also during the Permian and Jurassic. In the areas to the north and south, acidic igneous activity was predominant, although in some places basaltic activity was associated with deep fracturing. Folding was occurring intermittently through the Triassic, and flysch-like deposits are found in Lower Triassic strata. The Permian–Triassic boundary sequences can vary from geometrically conformable to unconformable, with formation of transgressive conglomerates. Similar trends have been reported in southern South America, but no marine deposition is known in the Lower Triassic strata.

In Chapter 18, Paull and Paull review the conodont faunas during the Lower Triassic. They recognize three periods of relative sea-level rise. They conclude that conodont faunas were virtually cosmopolitan during the Lower Triassic. That has important implications for correlations, and it also suggests widespread warm water temperatures and climates and the need for caution before identifying distinct provinces such as cold, temperate and tropical assuming water temperatures and climatic differences for such provinces, according to present world differences in climate.

In Chapter 19, Yin reports the distributions of various faunal and floral elements and their provincial distributions in eastern Asia. The sea was distributed north–south over that region, with no sea connection to the west through northern Asia, but with a relatively broad oceanic connection to the west through southern Asia, corresponding to the Tethys of Tournaisian.

Middle Triassic

Yin, in Chapter 19, shows a similar distribution of sea and land in eastern Asia and the continuation of a western connection through southern Asia.

In Vietnam, the Middle Triassic was a time of tremendous, largely acidic, igneous activity, and there were considerable changes in the distribution of basins, although not as many as in the Upper Triassic, when nonmarine deposition predominated (Dickins and Phan, Chapter 8, this volume).

In New Zealand (J. M. Dickins, personal observation) and in southern South America (López-Gamundi and Breitkreuz, Chapter 2, this volume), large-scale tectonic upheavals are indicated by the changed distributions of structures and sedimentations.

The adverse conditions for life that characterized the Permian–Triassic boundary continued in the Lower Triassic, as witnessed by a generally relatively low faunal diversity and an absence of reef development. Those conditions changed in the Middle Triassic, and Panina (Chapter 20, this volume) describes reef developments in Sikkote-Alin during the Middle and Upper Triassic. For descriptions of that change in the nature of carbonate deposition during the Triassic, see Flügel and Flügel-Kahler (1992) and Talent (1988).

Upper Triassic

Nowhere in all the Triassic were the changes more drastic than those that separated the Upper from the Middle Triassic. In Chapter 19, Yin tabulates the marked changes in the distribution of sea and land in eastern Asia. The events in Vietnam are reported in Chapter 8, and in the late Triassic the previously widespread marine sedimentation became confined to the western part of the Songda Depression, where it was connected westward with the Tethys swainway into western Asia and Europe. Eastern Southeast Asia formed a land area marking the eastern boundary of Tethys. In Vietnam, the positions changed again distinctly in the Lower Jurassic, whose strata are largely unconformable on Upper Triassic and earlier formations and are mainly nonmarine. In the southern part of Vietnam, a marine transgression took place from the south and east, either not connected or perhaps indirectly connected with Tethys (Phan, 1991b).

In Mexico, marine sedimentation began once again (González-León, Lucas, and Roldán-Quintana, Chapter 3, this volume) after a break following the Permian. That paralleled widespread deposition in the western United States (Miller and Harewood, 1990). Also in the nonmarine basins of the western United States, the Upper Triassic strata represent a distinctive period of time that Lucas (Chapter 23, this volume) proposes as a nonmarine standard for the Upper Triassic.

In Chapter 22, McRoberts discusses Halobia and its distribution in the uppermost Middle Triassic strata and the Upper Triassic strata. This bivalve is especially important for understanding the correlation of the marine rocks of that age and for discriminating between Middle and Upper Triassic strata.

The upper part of the Upper Triassic strata, the Rhaetian, has a distinctive development (Hallam, 1981; Hallam and El Shaarawy, 1982). In Chapter 24, Campbell discusses the marine fauna of that interval in New Zealand and its special character, as also found in other parts of the world.

Triassic–Jurassic boundary

The character of the Triassic–Jurassic boundary has been treated by Hallam (1981, 1990) and elsewhere in reports on Project 272 (Dickins, 1993a). Its significance is again emphasized in the trap volcanism identified by Sakhno (Chapter 17, this volume) in the Russian Far East. The worldwide significance of that tectonic and magmatic (as well as biological) event lies in the unique geochemistry of the basaltic volcanism that has been described by Puffer (1992). The basalts from eastern North America have the same predominant character as those from Morocco, southern Africa, southern South America, and Siberia. Puffer ascribed their character to rapid decompressive melting caused...
by an event “uniquely powerful enough to allow for rapid delivery of large quantities of unfractinated and uncontami-
nated magma directly from undepleted or enriched mantle
sources” (Puller, 1992, p. 95). There is also ample evidence for
that event in the basinal, stratigraphic, sedimentary, and biologic
changes at the Triassic–Jurassic boundary (Dickins, 1989, 1993a), no doubt reflecting major subcrustal changes in the
earth.

Climate

Although great climatic changes occurred during the late
Palaeozoic and early Mesozoic, the connections with the other
events outlined herein are not clear, nor are the connections with
other postulated changes, such as the formation and movement
of Pangaea.

In the early Carboniferous, the widespread areas of warm
and equable climate were reflected in cosmopolitan marine faunas.
The late Carboniferous apparently was generally cooler, but
there seems to have been at least one important warmer interval,
and at the beginning of the Permian, glaciation was widespread.
Warming took place during the Permian, so that by the beginning
of the Triassic there was a universally warm and largely dry
climate. A warm climate then continued into the Jurassic. Those
changes have been reviewed by Dickins (1993b) as part of
Project 272.

In Chapter 25, González gives a detailed account of the
changes in South America from the early Carboniferous to the
early Permian and the faunas that accompanied the various
phases. For the early Carboniferous he identifies a warm,
cosmopolitan fauna, replaced in the late part of the early
Carboniferous and the early part of the late Carboniferous by
the Levijuzula fauna associated with glacialis. For the upper-
most Carboniferous strata he reports fauna and sedimentation
patterns indicating warmer conditions, before a return to less
habitable conditions in the early Permian. Whether or not that
warm interval can be identified in other parts of the world is of
considerable interest. In Chapter 2, López-Gamundi and Breit-
kreuz describe the development of arid conditions later in the
Permian, and in Chapter 18, Pauli and Pauli, on the basis of the
cosmopolitan character of the conodont fauna, leave little
doubt that there was a widespread warm climate for the early
Triassic.

Yin (1991) has reviewed the palaeobiogeography of the
Triassic in China, and in Chapter 19 he describes the bio-
stratigraphy and the palaeogeography of eastern Asia during
the early, middle, and late Triassic. He describes the distribution
of sea and land — no sea through central Asia, but sea between
the present Himalayas and the Kunlun (often called Neotethys, but
the Tethys of Sues) — and the faunal and floral provinces and
discusses all that in relation to commonly held plate-tectonic
interpretations. Despite the widespread warm climate apparent
throughout the Triassic, he is able to delineate provinces, and
further examination of the meaning of those provinces could be
of great significance.

Discussion and conclusions

To understand geologic events, a reliable time scale that can be
made increasingly precise is a basic requirement. It has been
natural, therefore, for the participants in Project 272 to devote
considerable attention to biostratigraphic correlations. The way
toward further refinement of that scale has been indicated. The
radiometric data available from the Siberian traps have re-
vealed the difficulties associated with that method, and there is
a need for more radiometric work tied closely to sampling data
from well-established sequences dated stratigraphically and
palaeomagnetically.

The main purpose of these studies has been to look at those
circum-Pacific events in time and to assess the nature of the
events and the reliability and precision in their time assignments.
In some cases, analysis in terms of tectonic explanation has been
attempted, but the data are important not only for examining the
validity of existing theory but also because of their potential for
use in developing new approaches.

Some attempts have been made to examine the relationships
of metallogenesis to the other circum-Pacific events, and the
studies from Vietnam and the Russian Far East have been
particularly useful in indicating the relationships between peri-
odicities and other factors. Although, strictly speaking, they are
perhaps outside the scope of this project, the large-scale
polymetallic mineralizations associated with the magmatic and
tectonic events of the Cretaceous–Tertiary boundary are com-
monly encountered in Triassic carbonates. Such mineralization is
widespread in the circum-Pacific region close to the Cretaceous–
Tertiary boundary, and it has been extensively described for the

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2 Carboniferous-to-Triassic evolution of the Panthalassan margin in southern South America

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The continental margin of southern South America facing Panthalassa (or the proto-Pacific) has been characterized by subduction and transcurrent movements at least since mid-Palaeozoic times (Dalziel and Forsythe, 1985; Ramos, 1988a;Breitkreuz et al., 1989). Between the late Palaeozoic and the Triassic, that convergent margin subsided during synchronous stages of Pangean extension punctuated by diachronous subduction that formed a series of foreland basins by cratonward thrusting of the foldbelt/magmatic arc (Veevers et al., 1994). Those basins were formed by extension (E-I), subsequent foreland shortening (FS), and final extension (E-II). That tectonomagmatic evolution of the continental margin had subtler effects in the interior basins of South America, where sedimentation, although influenced, was not interrupted by major discontinuities. A key element in understanding that evolution is the presence of a rich stratigraphic record, mainly in western Argentina and northern Chile, spanning the Carboniferous–Triassic interval that helps to identify the transition from a compressional to an “extensional” convergent margin. The objective of this chapter is to synthesize our current knowledge of the evolution of the Panthalassan margin of southern South America during the late Palaeozoic and Triassic. For detailed descriptions and discussions, the reader is referred to the numerous publications cited.

On the basis of distinct characteristics to be described later, the convergent margin of South America can be subdivided into three segments (Figure 2.1), namely, (A) a northern segment (north of 20°S), (B) a central segment (20–40°S), and (C) a southern segment (south of 40°S) (López-Gamundi et al., 1994).

Northern (A) segment. The Devonian-to-Permian evolution of the northern segment was mainly controlled by the interaction between the Arequipa Massif, a Precambrian basement block, and the South American continent, with periodic episodes of extension and compression/transpression (Forsythe et al., 1993). In western Bolivia and southwestern Peru, Devonian and younger deposits rest on a basement largely composed of Precambrian intrusives and high-grade metamorphic rocks of the Arequipa Massif and adjacent parautochthonous terranes (e.g., Mejillones, Belén) in northern Chile. Palaeocurrent evidence from early Palaeozoic deposits of that ensialic seaway suggests that the Arequipa Massif constituted the main provenance terrane (Isaacs, 1975). During the late Devonian and early Carboniferous the E-Hercynian Orogeny affected the deposits presently exposed in the Eastern Cordillera of Perú and Bolivia (Lauhacher and Megard, 1985). The Tarija foredeep basin (Figure 2.1), developed since the Carboniferous, was emplaced over the axis of the early Palaeozoic basin between the Arequipa Massif and the Brazilian Shield.

Central (B) segment. Formation of this segment was characterized by subduction and associated arc magmatism. In the northern part (20–27°S), magmatism did not start until the late Carboniferous. There, magmatic (intrusive and extrusive) activity lasted until the Triassic, a time span during which volcanic-sedimentary successions up to 4 km thick (Péine Group) (Bahlburg and Breitkreuz, 1991) were formed. Earlier, during the Devonian and early Carboniferous, a marine marginal basin existed in northern Chile between the southernmost part of the Arequipa Massif on the west and the Puna Arch on the east (Niemeyer et al., 1985; Bahlburg, 1991). Its formation, locally accompanied by marine rift volcanism (Breitkreuz et al., 1989), and later closure were most likely controlled by north-south-trending dextral strike-slip movements (Bahlburg and Breitkreuz, 1991, 1993).

In the southern part of the central segment, between 27°S and 40°S, an Andean-type continental margin developed, probably as early as during the Devonian. Well-preserved accretionary prism sequences (Davidson et al., 1987; Hervé, 1988) and tectonic mélanges (Dalziel and Forsythe, 1985) indicate the presence of a subduction complex along that part of the continental margin. The inception of a subduction-zone-related magmatic arc occurred most probably in the late Devonian, and back-arc basins developed later in the late Palaeozoic. Although terrane collision has been proposed as an important factor in the development of that margin during the early and middle Palaeozoic (cf. Ramos et al., 1986), other views tend to minimize its influence (Charrier et al., 1991; González Bonorino and González Bonorino, 1991).
Southern (C) segment. South of 43°S, the Panthalassan continental margin mostly resulted from accretion of terranes, like the one represented by the Permian limestones of the Madre de Dios Archipelago of southern Chile (Mpodozis and Forsythe, 1983; Dalziel and Forsythe, 1985). The late Palaeozoic magmatic arc that developed along the middle segment of the continental margin extended southward, being deflected into the continent, as indicated by the presence of coeval, crust-contaminated magmatism in Patagonia. That southeastward swing of the magmatic tract occurred along a line coincident with the old Gondwanan margin. Forsythe (1982) and Uliana and Biddle (1987) related that magmatic activity in the North Patagonian Massif to the presence of an Andean-type margin with a wide magmatic-arc–back-arc system across Patagonia (Figure 2.1). This wide system has been subdivided into an outer arc with metaaluminous granitoids and an inner arc with peraluminous and weakly metaaluminous granitoids and silicic volcanics (Cingolani et al., 1991). Associated sedimentation in fore-arc settings is exemplified by the thick (>5,000 m) sequence of the Tepuel Basin in western Patagonia (Figure 2.1).
Alternatively, Ramos (1984, 1986) related the late Palaeozoic magnatism in Patagonia to a collisional model. This model proposes a south-westward-dipping subduction zone under a separate Patagonian plate in the context of a continent–continent collision. However, the available evidence from radiometric dates (Cingolani et al., 1991), palaeomagnetic data (Rapalini et al., 1993), palaeogeographic aspects, and the continuity of the magmatic belt (López-Gamundi et al., 1994) favors autochthony of Patagonia since at least the Carboniferous.

The continental-margin evolution occurred under a drastic palaeoclimatic transition characterized by widespread glaciation during the mid-Carboniferous, followed by climatic amelioration evinced by the presence of extensive peats during the late Carboniferous, culminating with arid to semi-arid conditions, illustrated by the presence of red beds with eolian deposits in the middle to late Permian (López-Gamundi, Limarino, and Cesari, 1992). The combination of high palaeolatitude and high relief induced the onset and development of the mid-Carboniferous glaciation along the Andean basins of southwestern South America. That glacial episode preceded the generalized glaciation that affected eastern South America, Africa, and Antarctica during the latest Carboniferous and early Permian (Figure 2.2). After a moderately humid interlude during the latest Carboniferous and early Permian, extremely arid conditions induced the development of extensive sand seas behind the continental margin in western Argentina by the middle to late Permian (Limarino and Spalletti, 1986). A similar trend, although starting in the early Carboniferous with glacial deposits followed by mid-Carboniferous deposits and culminating with platform carbonates in the early Permian, has recently been documented from the Antiplano of Bolivia (Sempere, 1987; Díaz Martínez, Isacson, and Sablock, 1993).

In the following sections we review the evolution of this margin between 20°S and 38°S during the Carboniferous–Triassic time interval, a sector roughly coincident with segment B as defined earlier. To this end, we review the existing stratigraphic and structural information on the Argentinian and northern Chilean outcrops and document the evolution of that portion of the Panthalassan margin.

Initial extension (and middle Carboniferous to early Permian)

Early–middle Carboniferous: orogeny and inception of the magmatic arc

Late Devonian–early Carboniferous unconformity. A widespread unconformity that separates Lower and Middle (Devonian) Palaeozoic marine deposits from marine to nonmarine Carboniferous deposits is thoroughly documented in southern South America. In southeastern Perú and Bolivia, Devonian marine sediments tightly folded during the Eo–Hercynian orogenic phase (Dalmyray et al., 1980) are overlain by early Carboniferous coarse deposits (Laubacher and Megard, 1985). This