Inverse relation between ice extent and the late Paleozoic glacial record of Gondwana

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ABSTRACT

The late Carboniferous–earliest Permian age estimate (300–280 Ma) for maximum ice volume during late Paleozoic glaciation of Gondwana is challenged. Past estimates assume a direct relation between extent of depositional glacial record and former ice cover; this assumption cannot be sustained, given that the glacial record is composed predominantly of glacially influenced marine strata that accumulated on the margins of ice-covered areas. We argue that Gondwana ice cover expanded in the Early Carboniferous in response to polar position, availability of moisture from a mediterranean sea, and epeirogenic uplift of the Gondwana interior. In Namurian time (ca. 325 Ma), Gondwana ice cover attained a maximum extent of about 21 × 10^6 km^2, nearly the area of maximum Pleistocene ice cover. Despite extensive ice cover, the depositional record is meager; continental glacial deposits are poorly preserved on a regional unconformity. Thereafter, extensional subsidence of intracratonic basins promoted marine flooding, fragmentation of the ice cover, and the accumulation of thick glacially influenced marine deposits. In Stephanian-Asselian time (ca. 285 Ma), ice cover had decreased to about 15 × 10^6 km^2, but glacial marine strata were being deposited and preserved across a very large area of the Gondwana supercontinent.

INTRODUCTION

Upper Paleozoic glacial deposits increase from minimal volume and extent in the lower Carboniferous to maximum volume and geographic distribution in the uppermost Carboniferous to lowermost Permian (e.g., Frakes et al., 1992). Several authors have interpreted this trend as evidence for maximum ice cover in the latest Carboniferous to earliest Permian (Bambach et al., 1980; Veevers and Powell, 1987; Frakes et al., 1992). We argue in this paper that the geographic distribution of the glacial record in Gondwana is not simply related to ice volume and extent, because large continental ice sheets leave a meager terrestrial depositional record. Instead, regional tectonics, in particular the subsidence of intracratonic basins across Gondwana, was a major factor in controlling the distribution and preservation of the glacial record. We argue herein that maximum ice cover occurred in the mid-Carboniferous but that maximum extent of glacial marine sedimentation took place subsequently, in the late Carboniferous to earliest Permian, reflecting widespread intracratonic subsidence that allowed the deposition and preservation of the thick and extensive glacially influenced marine strata that dominate the glacial record.

LATE PALEOZOIC TECTONICS AND GEOGRAPHY OF GONDWANA

In the latest Devonian and Early Carboniferous, Gondwana underwent epeirogenic uplift and inversion of early Paleozoic pericratonic and intracratonic sedimentary basins (Eyles, 1993). Preexisting intracratonic highlands persisted into the late Paleozoic (Australia—Veevers et al., 1984; western South America—González-Bonorino, 1991; South Africa—Visser, 1993). Subaerial exposure of much of Gondwana is reflected in a widespread unconformity (Fig. 1A) that separates lowermost Carboniferous and older strata from Namurian to Stephanian deposits (Veevers and Powell, 1987). Regional uplift can be mainly ascribed to intraplate compressional stresses originating in protracted collisions with Laurussia (Variscan orogeny, Fig. 2; Ziegler, 1988), as well as cratonward subduction and microcontinent collisions along the Pacific margin (northeast Africa—Klitzsch, 1990; Antarctica—Findlay, 1991; Chile-Argentina—Ramos, 1994).

Visean to earliest Namurian marine foreland basins developed along the Pacific margin (Fig. 1A; Ramos et al., 1986, South America; Veevers et al., 1984, Australia). Terrestrial deposits of this age in northern Chile and central-western Argentina (González-Bonorino, 1991) and in eastern Australia (Brown et al., 1983) indicate local emergence above sea level of a Pacific orogen. In western South America, orogenic relief was, however, largely drowned by the Namurian sea (González-Bonorino, 1991).

In Westphalian to Stephanian time, the development of intracratonic basins and plate-margin rifting reflect a change to an extensional stress regime (e.g., Australia—Veevers et al., 1984; India—Gupta and Brookfield, 1991; South America—Eyles et al., 1993), following the end of the Variscan orogeny (cf. Ziegler, 1988) and the waning of diastrophism in the Alleghanian orogen (Hatcher et al., 1989; Fig. 2). Stress relaxation at this time has also been documented for the European plate (Becq-Giraudon and Van Den Driessche, 1994). At the Pacific margin the Transantarctic foreland basin formed at this time (Sahagian and Collinson, 1993), and by the late Stephanian to Sakmarian, extension had spread across Gondwana and new intracratonic basins developed in Egypt, Arabia, India, and western Australia by subsidence of cratonic blocks girdled by Late Proterozoic mobile belts (Eyles, 1993).

In summary, elevation of Gondwana in the early part of the Carboniferous was followed by the initial subsidence of foreland basins of western South America and eastern Australia in Visean to Namurian time (345–325 Ma) and subsequently intracratonic basins and the Transantarctic foreland basin during Westphalian to Asselian time (310–280 Ma; Fig. 2, basin tectonics). The

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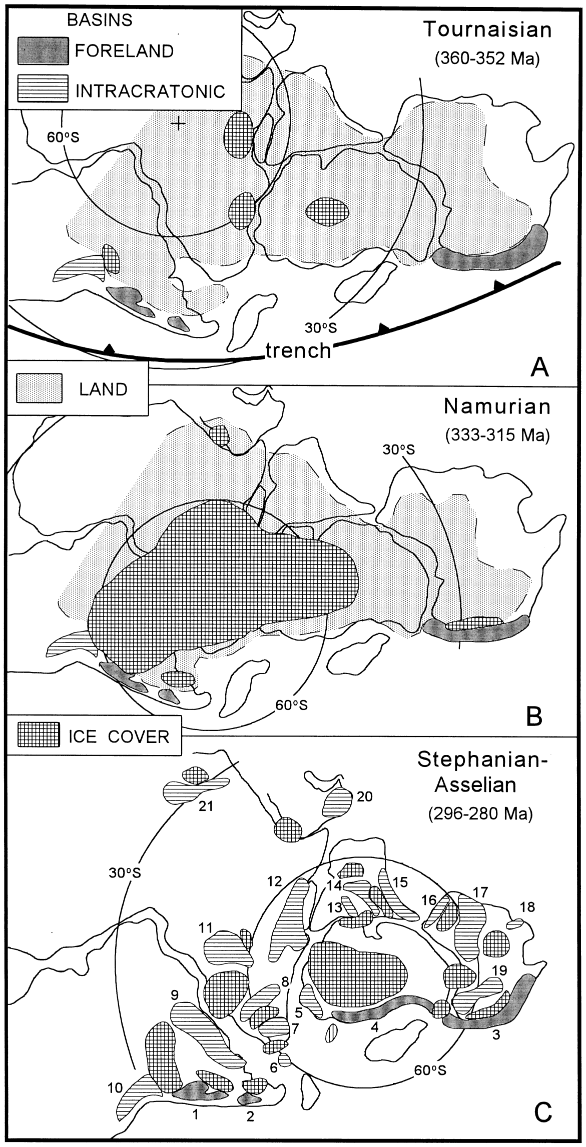

Figure 1. Schematic representation of geography and ice cover in Gondwana in late Paleozoic time. Continental arrangement and paleopolar position based on Dalziel (1992) and Ramos (1994). Glaciated basins: 1—Paganzo-Maliman; 2—Tepuel; 3—Bowen, Sydney, Tasman; 4—Transantarctic-Ellsworth; 5—Queen Maud; 6—Malvinas-Falklands; 7—Karoo; 8—Kalahari; 9—Parana, Chaco, Ventana; 10—Chaco-Tarija; 11—Congo; 12—Tanzania, Zambia, Madagascar; 13—Godavari; 14—Damodar, Mahanadi; 15—Himalayas; 16—Carnarvon, Perth; 17—Canning, Officer; 18—Bonaparte; 19—Murray, Galilee; 20—Oman; 21—southwest Egypt. Main data sources: 1, 2, 9, 10—González-Bonorino (1991, 1992), Eyles et al. (1993, 1995); 3, 16, 17, 18, 19—Brown et al. (1983), Veevers et al. (1984), Brakel and Totterdell (1993); 4—Barrett (1991), Findlay (1991); 7, 8—Visser (1989, 1993); 11, 12—Eyles (1993); 13, 14, 15—Gupta and Brookfield (1991); 20—Levell et al. (1988); 21—Klitzsch (1990).

pattern and timing of regional subsidence across Gondwana are key to understanding the glacial record and its relation to ice extent.

GLACIAL RECORD

The oldest glacial record for the late Paleozoic consists of Tournaisian glacial marine deposits in the northwestern Chaco-Tarija basin in western South America (Eyles et al., 1995; glaciated basins are identified in Fig. 1C). As yet there is no confirmed glacial record for the Visean to early Namurian. Mid-Namurian to lower Westphalian deposits are found in the foreland basins of South America (Frakes and Crowell, 1969; González-Bonorino, 1991, 1992) and eastern Australia (Brown et al., 1983).

Considerable thicknesses of upper Westphalian to lower Stephanian marine and lacustrine glacial deposits are found in all foreland basins and in intracratonic basins in South America, central and southern Africa, and southeastern Australia (Veevers and Powell, 1987; Visser, 1989; Barrett, 1991; Eyles et al., 1993, 1995). Younger, upper Stephanian to mid-Sakmarian marine and terrestrial glacial deposits occur in the intracratonic basins in Egypt (Klitzsch, 1990), Arabia (Levell et al., 1988), India (Gupta and Brookfield, 1991), and western Australia (Veevers et al., 1984). Widespread transgression in Sakmarian time accompanied the end of extensive glacial sedimentation in Gondwana (Veevers and Powell, 1987).

Measurement of the area covered by glacial deposits of different ages shows that the Gondwana glacial record is a minimum in the Tournaisian, covers about 0.1×10^6 km^2 in the Namurian, reaches a maximum of about 12×10^6 km^2 in the Stephanian-Asselian, and then decreases into the upper Sakmarian (Fig. 2, glacial record).

PREVIOUS INTERPRETATIONS

The Namurian to Sakmarian stratigraphic trend in the extent and geographic distribution of the upper Paleozoic glacial record has been previously interpreted as reflecting a similar trend in Gondwana ice cover and volume. In this view the restricted Namurian glacial record of the foreland basins indicates the growth of mountain and piedmont glaciers on the Pacific orogen, and the extensive younger record implies the development of ice sheets in the Gondwana interior in response to continental drift (Bambach et al., 1980; Veevers and Powell, 1987; Frakes et al., 1992). In contrast to this interpretation, the existence of glaciated mountain ranges in the Namurian cannot be substantiated in western South America where, in fact, there is firm evidence for ice movement from the craton interior *toward* the Pacific (González-Bonorino, 1991, 1992).

Glaciated basins in Gondwana are organized (Fig. 2, older record) according to the age of the older glacial fill. Initial Namurian glacial deposits occur in foreland basins that were flooded in the Visean–early Namurian; later glacial deposits of upper Westphalian–lower Stephanian age occur in the Transantarctic foreland basin and in intracratonic basins occupying central positions in Gondwana; and younger glacial deposits of upper Stephanian–Asselian age occur in intracratonic basins on the opposite flank of Gondwana. Thus, the glacial record expanded away from the Pacific margin—i.e., *transverse* to the polar track (see south pole positions in Fig. 1). In intracratonic basins, and in cratonward portions of foreland basins, thick accumulations of glacial deposits rest directly on eroded Devonian and older strata, suggesting that these areas had not been previously flooded in the late Paleozoic. The stratigraphic information thus shows that the distribution of the Namurian-Sakmarian glacial record was largely dictated by regional tectonics and the timing of basin subsidence and not simply by the migration of glacial centers.

VARIATIONS IN GONDWANA ICE COVER

Initial accumulation of ice commenced in the early part of the Carboniferous when Gondwana was undergoing epeirogenic uplift. A Tournaisian ice cap would have fed glaciers in the Chaco-Tarija basin (Fig. 1A). The paucity of the glacial record of this age is not surprising given the low preservation potential of terrestrial glacial products

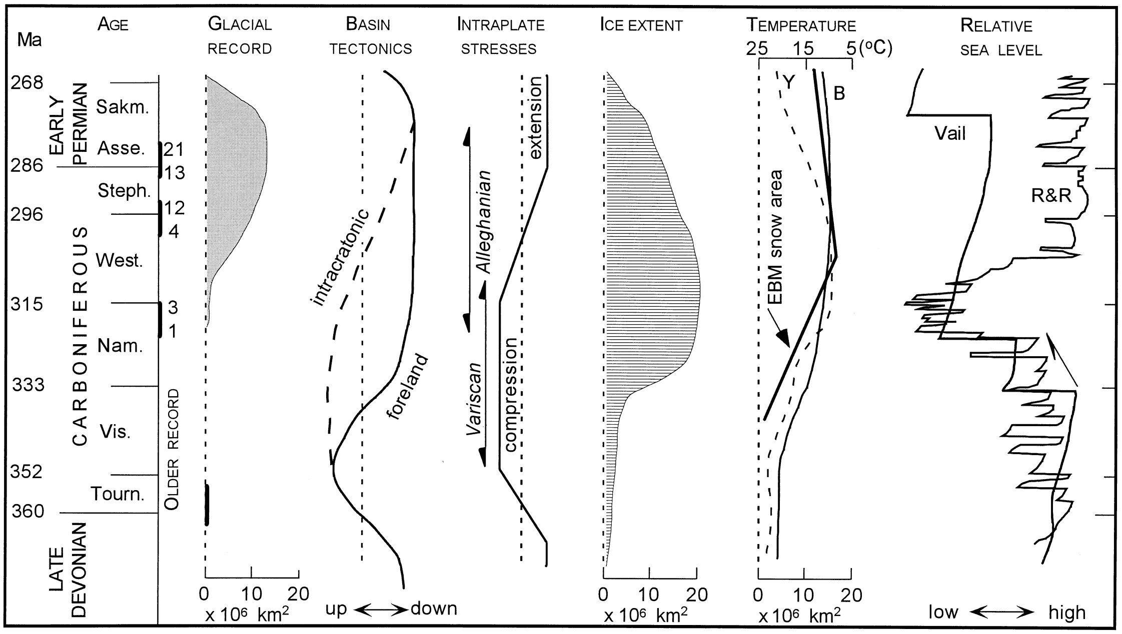

Figure 2. Summary data involved in estimate of Gondwana ice-covered area. Time scale is from 1989 Geological Society of America Decade of North American Geology. Significance of columns: Older record—oldest glacial deposits in basins indicated by range of numbers; glacial record—areal extent of terrestrial and glacial marine deposits; basin tectonics—uplift-subsidence history for first-generation foreland basins (1 to 3) and intracratonic basins; intraplate stresses—stress regime in Gondwana interior with approximate durations of Variscan and Alleghanian orogenies (Ziegler, 1988); ice extent—continental ice cover on Gondwana; EBM snow area—energy-balance model estimates of summer snow area in Gondwana (from Crowley and Baum, 1992); temperature—Y is neritic sea-water temperatures at low to intermediate latitudes based on Ca/Mg (from Yasamanov, 1981), and B is modeled atmospheric temperatures (from Berner, 1994); relative sea level—Vail = Vail et al. (1977), R&R = Ross and Ross (1988).

(about 94% of the glacial record is marine; Eyles, 1993).

Namurian ice-contact marine deposits in the Paganzo-Maliman and Tepuel basins (González, 1981; González-Bonorino, 1991, 1992) attest to the presence of ice cover at the paleo-Pacific freeboard of Gondwana. Much of Gondwana, from western South America to India, may have been covered by ice in the Namurian (Fig. 1B). Later, as basins subsided and were flooded by seawater, the ice-covered area was progressively reduced and replaced by areas of marine glacial sedimentation.

Namurian ice cover was maximum in the late Paleozoic (Fig. 1B). Expansion probably was the result of moisture available from marine areas in polar latitudes (Crowell and Frakes, 1975; Crowley and Baum, 1991) and high continental elevation at the time when the effects of the Variscan and Alleghanian orogenies overlapped (Fig. 2). The ice-covered area is estimated at $\sim 21 \times 10^6$ km^2 (Fig. 2), close to that of maximum Pleistocene ice cover (23.5×10^6 km^2, according to Crowley and Baum, 1991).

In late Westphalian–early Stephanian time (305–290 Ma), ice covers were limited to emergent highs separating actively subsiding basins in central Gondwana. By late Stephanian–Asselian time (290–275 Ma), widely separated ice covers lay on the margins of glacially influenced marine areas extending to Arabia, India, and western Australia (Fig. 1C). The total ice-covered area may have decreased to about 12×10^6 km^2 at this time (Fig. 2), an area similar to that of the present ice cover in Antarctica.

DISCUSSION

The argument presented herein for maximum late Paleozoic ice extent in Namurian time is supported by: (1) data that indicate global cooling from the Late Devonian into the middle part of the Carboniferous (Frakes et al., 1992) and minimum seawater temperatures in Namurian to Westphalian time, followed by slow warming into the Early Permian (estimates by Yasamanov, 1981, Ca/Mg in shells; Fig. 2, temperature, Y; Ross and Ross, 1988, study of fauna and carbonate production; and Grossman, 1994, oxygen isotopes); (2) biotic migration patterns reflecting high-latitude cooling in Namurian time (Raymond et al., 1989); (3) numerical modeling of atmospheric temperature (Berner, 1994, Fig. 2, B); and (4) energy-balance modeling suggesting rapid increase in summer snow cover from the mid-Visean to the mid-Westphalian, followed by slow decrease into the Early Permian (Crowley and Baum, 1992; Fig. 2, EBM snow area).

Our estimate of ice-cover expansion in the early part of the Carboniferous to a maximum in the Namurian is therefore consistent with published paleotemperature data and with the results of climate modeling. We suggest that increasing ice volumes in the early Carboniferous are reflected in the drawdown in relative sea level recorded in the early Namurian (Fig. 2).

Subsequent reduction of the ice cover during approximately Westphalian time reflects subsidence and marine incursions into Gondwana rather than any rise in global temperatures. Transgression greatly increased the glacially influenced marine areas and resulted in the preservation of a very large volume of glacial marine strata.

CONCLUSIONS

An inverse relation between ice extent and deposit extent is identified for late Paleozoic glaciation. Ice cover in Gondwana expanded from minimal values in the earliest Carboniferous to a maximum in the Namurian to early Westphalian, accompanying a global cooling trend and favored by an elevated continent. At maximum extent Gondwana ice cover was close to that of maximum Pleistocene ice cover. However, this early stage of glaciation on Gondwana is only poorly represented by the depositional record because the ice was land based and deposits are poorly preserved. From the Westphalian into the Sakmarian, ice cover gradually decreased as a result of fragmentation due to basin formation and marine flooding of glaciated areas of Gondwana. Regional subsidence allowed the preservation of a thick and widespread glacially influenced marine record.

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