PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Palaeoclimate, Sedimentation and Continental Accretion [and Discussion]

A. M. Ziegler, S. F. Barrett, C. R. Scotese and B. W. Sellwood

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Palaeoclimate, sedimentation and continental accretion

By A. M. Ziegler, S. F. Barrett and C. R. Scotese
Department of the Geophysical Sciences, The University of Chicago, Chicago, Illinois 60637, *U.S.A.*

Climate has a pervasive effect on sedimentation today, and the same climatic patterns are reflected in the distribution of lithofacies through the Palaeozoic, as the continents migrate beneath the climatic zones. The low-latitude hot wet zone is represented by thick clastics, coals and carbonates and is best developed along east coasts where prevailing winds bring moisture and heated surface waters toward the continent. The desert zones occur on the west sides of continents centred at 20° north and south, and these dry belts are represented in the geological record by evaporites. Tillites, thick clastics and coals occur in the temperate rainy belts, especially on the windward, west sides of continents above 40° latitude.

Continental accretion occurs where subduction zones coincide with rainy zones, such that the products of erosion are transported to the trench, and thus thrust back, extending the margin of the continent. The opposite process of 'tectonic erosion', wherein the descending oceanic slab continually 'rasps' away the margin of the continental crust, may occur in areas where rainfall and surface run-off is insufficient to provide trench sediments. This process has been operating adjacent to the Atacama Desert in South America during the past 200 Ma. To judge by the eastward migration of the calc-alkaline intrusive foci, about 250 km of the margin of South America have been transported down the subduction zone during this period.

Introduction

Palaeogeographers initially became interested in the distribution of climatically sensitive sediments as a means of confirming their reconstructions (Wegener 1929; Briden 1968, 1970; Drewry *et al.* 1974; Ziegler *et al.* 1977, 1979). The purpose of the present paper is to stress that most sediment types bear a strong climatic imprint, and, moreover, that the amount of rainfall indirectly affects whether continents grow through accretion or become 'tectonically eroded'. Palaeoclimatology should therefore be of more than a passing interest to stratigraphers or, for that matter, tectonicists. This is particularly so because rainfall patterns and temperature gradients are eminently predictable by means of the more accurate palaeogeographic maps now appearing in the literature.

In this paper we use South America as a present-day example to relate rainfall patterns, topography, sediment types and the balance of accretion and tectonic erosion. We then examine these effects in the Palaeozoic by means of data derived from a set of recently published world-wide palaeogeographic reconstructions (Ziegler *et al.* 1979).

Present-day South America

The Andean chain of South America is ideal as a case study in climatology because of its north–south orientation and length, which spans the equatorial rainy zone, the subtropical desert zone, and the south temperate rainy belt. Moreover, South America has remained within 10° of its present latitude since the early Jurassic (Smith & Briden 1977), so that the effects related to these climatic zones have been cumulative over a period of 200 Ma. Further,

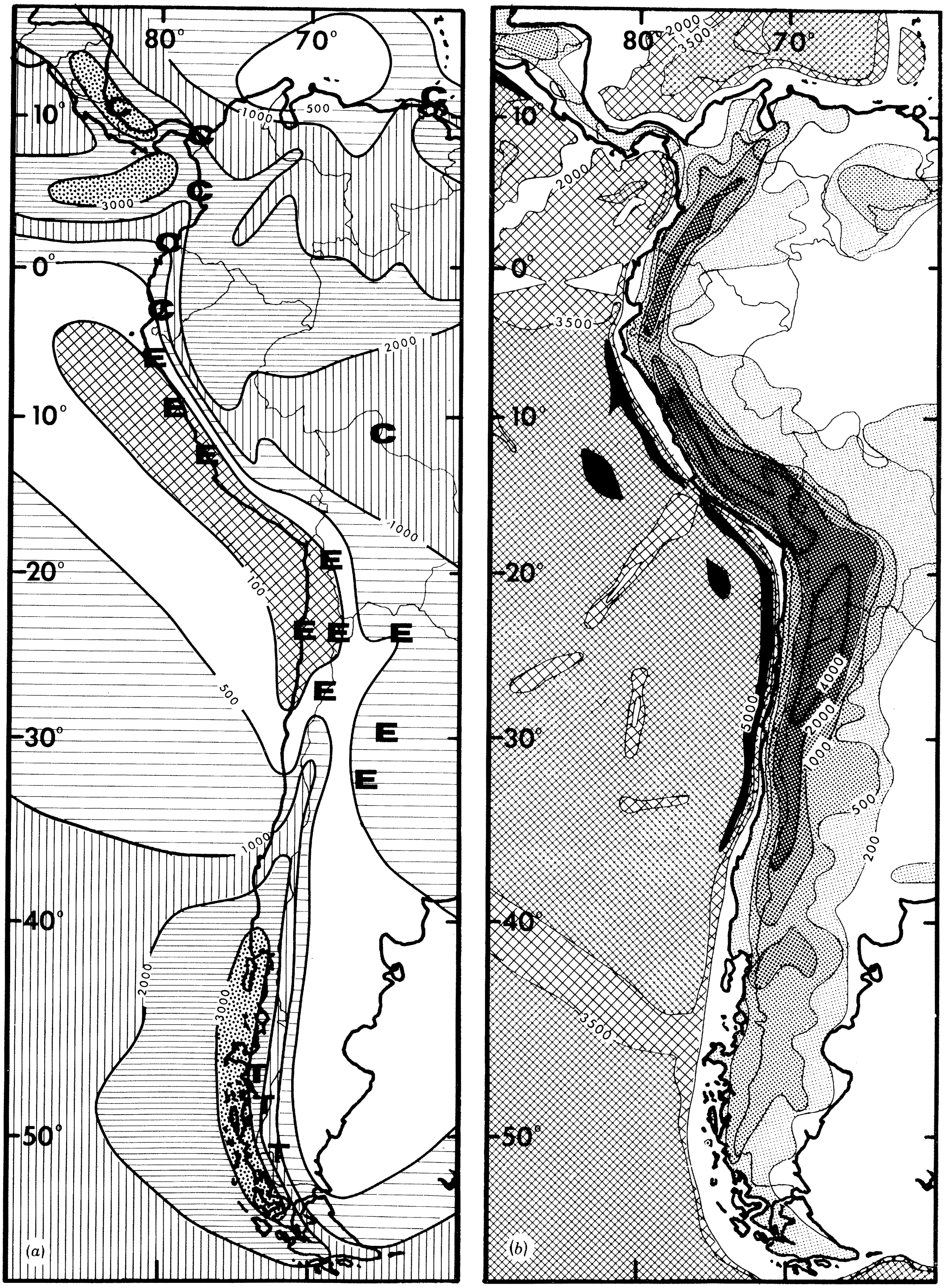

FIGURE 1. Western South American annual rainfall (*a*) and topography (*b*). The rainfall (in millimetres) is from an unpublished world map prepared by T. T. Fujita, University of Chicago, and incorporates ground-based measurements as well as mean annual cloud patterns determined from satellite data. Also shown on this map are presently forming coal swamps (Schmithusen 1976), evaporites (LeFond 1969), and glacial tills (de Almeida 1978) represented by the letters C, E, and T respectively. The topography (in metres) was generalized by averaging the height per 1° latitude–longitude square and recontouring (from the U.S. Department of Defense map, *The World*, 1971, 1:11 million). The bathymetric contours were smoothed somewhat (from the U.S.S.R. map, *Relief of the Pacific Ocean*, 1964, 1:10 million).

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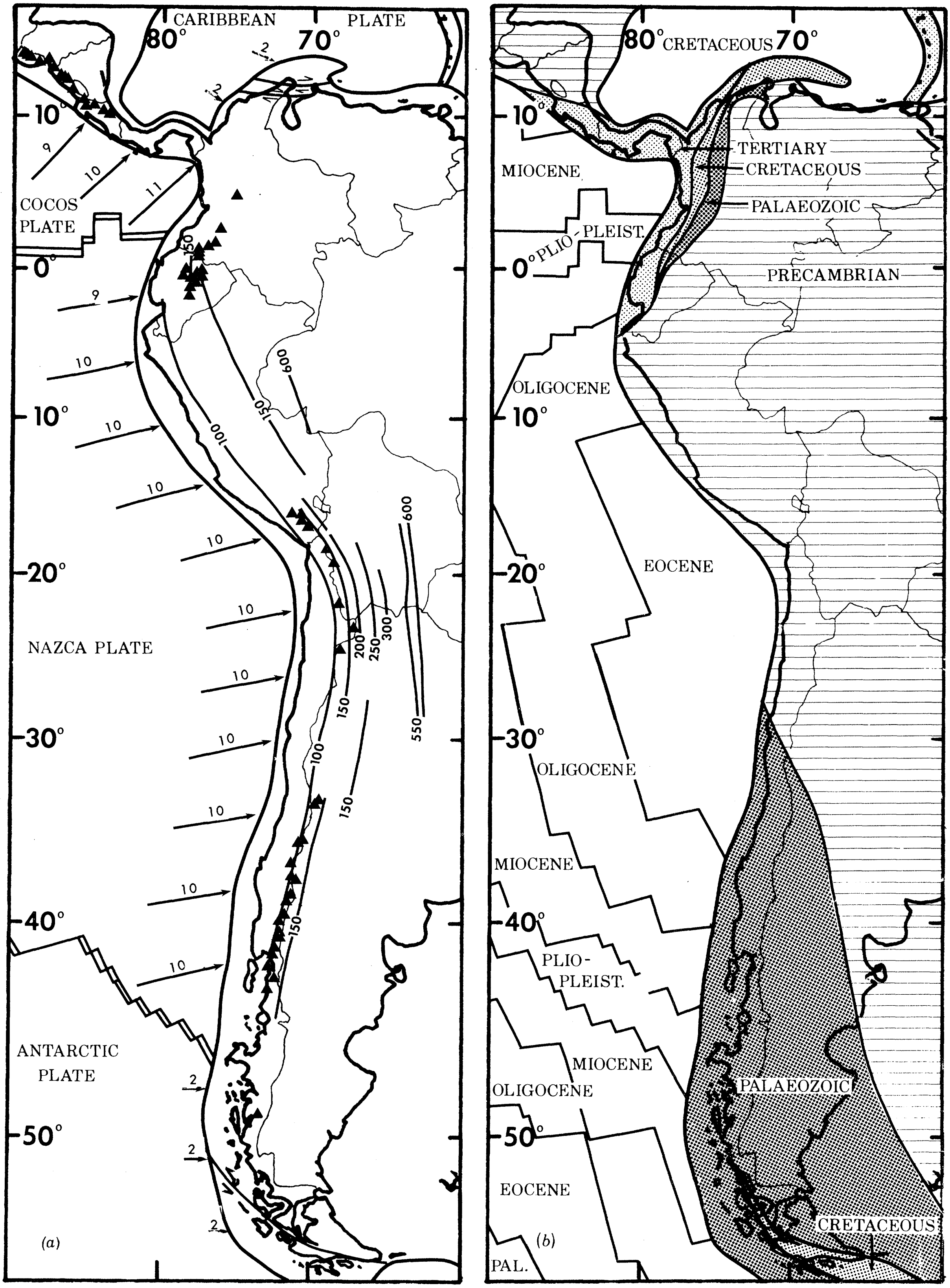

FIGURE 2. Western South American plate tectonic relationships (*a*) and oceanic and continental crust ages (*b*). Relative plate motions (in centimetres per year) were calculated from Minster & Jordan (1978). Depth contours (in kilometres) of the descending Nazca plate beneath South America taken from Barazangi & Isacks (1976). Active volcanoes are represented by triangles (McDonald 1972). The age of the oceanic crust has been modified from Pitman *et al.* (1974) by means of the maps of Hey *et al.* (1977), Herron & Tucholke (1976) and Sclater (personal communication). The locations of the continental accretion zones were determined from Arango Calad *et al.* (1976), Dalziel *et al.* (1975), de Almeida (1978), Dewitt (1977), Herve *et al.* (1974), Irving (1975) and McBride *et al.* (1976).

the boundaries of these climatic zones occur at the same latitudes as the boundaries of the tectonic zones (Gansser 1973; Zeil 1979), and one of our purposes is to point out that this is more than pure coincidence.

Rainfall and relief are negatively correlated in the Andes (figure 1). In both the tropical and temperate rainy zones the mountains are reduced and the offshore trench is relatively full of sediment (Hayes 1974). The intervening Atacama Desert is the driest in the world and here 'the Andean mountain range climbs to elevations of about 7 km and, in concert with the trench system, defines some of the largest regional topographic gradients found anywhere in the world' (Hayes 1974). The Atacama Desert, like other coastal deserts of the world, past and present, ranges from about 5 to 30° from the equator. We point this out because some have argued that the dry conditions are present because of the high elevations rather than vice versa. Certainly, a 'positive feedback system' is in operation, but even without mountains, the dry air associated with the descending limbs of the Hadley cells at these latitudes is a phenomenon that transcends local orographic effects.

It would suit our purposes if plate-tectonic relationships were constant over the entire latitudinal span of the Andes, but this, unfortunately, is not so (figure 2). Because four oceanic plates impinge on the western margin of South America, the relative motions vary, as do the ages of the ocean floor. In addition, portions of the same plate dip at different angles beneath the Andes, and it is only the more steeply dipping slabs that seem to generate volcanism (Barazangi & Isacks 1976). Despite these heterogeneities, all the oceanic plates have a landward component of motion and this results in the accretion of trench deposits in Colombia and Ecuador (Irving 1975; Barrero-Lozano 1979; Henderson 1979), an area of high rainfall, rapid erosion, and present-day active sedimentation in the adjacent trench. An accretionary belt 300 km wide including Palaeozoic, Cretaceous and Tertiary oceanic rocks is evident in this equatorial region. By contrast, in the desert regions of Peru and northern Chile rocks nearly 2 Ga old crop out along the coast (Cobbing *et al.* 1977; Dalmayrac *et al.* 1977), within 70 km of the present inner trench wall. Further south, in the temperate rainy zone, one might expect a Tertiary accretionary belt, but none is evident, though Palaeozoic (Herve *et al.* 1974; McBride *et al.* 1976; DeWitt 1977) and Mesozoic (Dalziel *et al.* 1975) accretion may be inferred.

To test the notion that accretion has occurred in some parts of the Andes, we plotted the radiometrically determined ages of calc-alkaline intrusions along the entire chain (figure 3*a*). In Colombia and Venezuela the intrusive foci move seaward through the Mesozoic and Cainozoic in parallel with the accretionary zones (Irving 1975; Shagam 1972). In fact, the later plutons intrude the earlier accreted wedges. By contrast, in Peru and northern Chile, where no accretion is evident, Jurassic plutons intrude the Precambian rocks along the coast, and the younger grandiorite belts occur progressively inland to the point where they coincide with the present calc-alkaline volcanoes (Farrar *et al.* 1970; Aguirre *et al.* 1974). The process of 'tectonic erosion', whereby the margin of the continent is 'rasped' by the underthrusting ocean plate, has been invoked to account for this pattern (Plafker 1972; Helwig 1972). It has been stated that in southern Chile and Argentina 'no systematic unidirectional migration of radiometric ages is observed' (Halpern & Fuenzalida 1978), nor has Tertiary accretion been detected. Possibly the rate of convergence of the Antarctic plate, which is one-fifth of that of the other Pacific plates relative to South America, is too slow to result in accretion. The Mesozoic plutonic patterns of this region are complicated by trans-current faulting and the proposed existence of a marginal basin with plutons associated with both sides (Dalziel *et al.* 1975).

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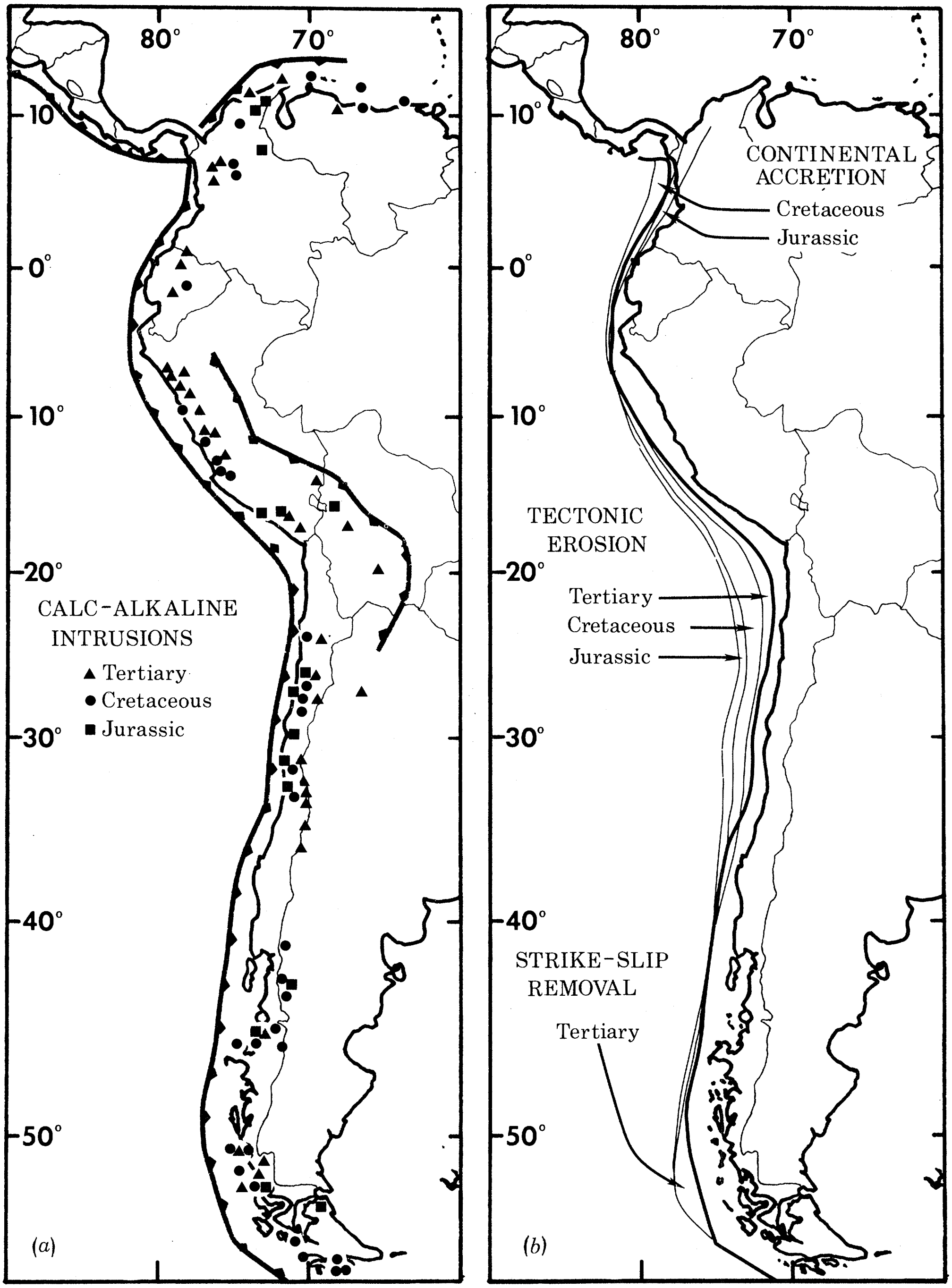

Figure 3. Western South American calc-alkaline intrusions (*a*) and continental margins (*b*) for the Jurassic through the Tertiary. The ages of the calc-alkaline intrusions were assembled from the radiometric data (in order from north to south) of Santamaria & Schubert (1974), Irving (1975), Stewart *et al.* (1974), Evernden *et al.* (1975), Farrar *et al.* (1970), Caelles *et al.* (1971), Aguirre *et al.* (1974), Drake (1976), Halpern & Fuenzalida (1978), Halpern (1973), Halpern & Carlin (1971), and Halpern & Rex (1972). The present continental margin is shown by the heavy line and earlier margins by the light lines. The earlier margins were determined by assuming that they were located 300 km seaward of their respective calc-alkaline intrusive belts.

With reference to the entire Andean chain we conclude that accretionary prisms are forming, or are at least preserved, in the areas where rainfall is sufficient to erode sediments and transport them to the trench, and where underthrusting of the oceanic plate is relatively rapid. Where no sediments are provided to the trench and underthrusting is rapid, the oceanic plate encounters and subcrustally erodes the continental crust. We reject the suggestion that the central portions of the margin of South America have been removed by rifting or by transcurrent faulting (Cobbing *et al.* 1977) because of the relative motion of the Nazca Plate, which at present, at least, is directly onshore. We feel that tectonic erosion is the only viable means of explaining the very gradual inward migration of the granodiorite intrusions.

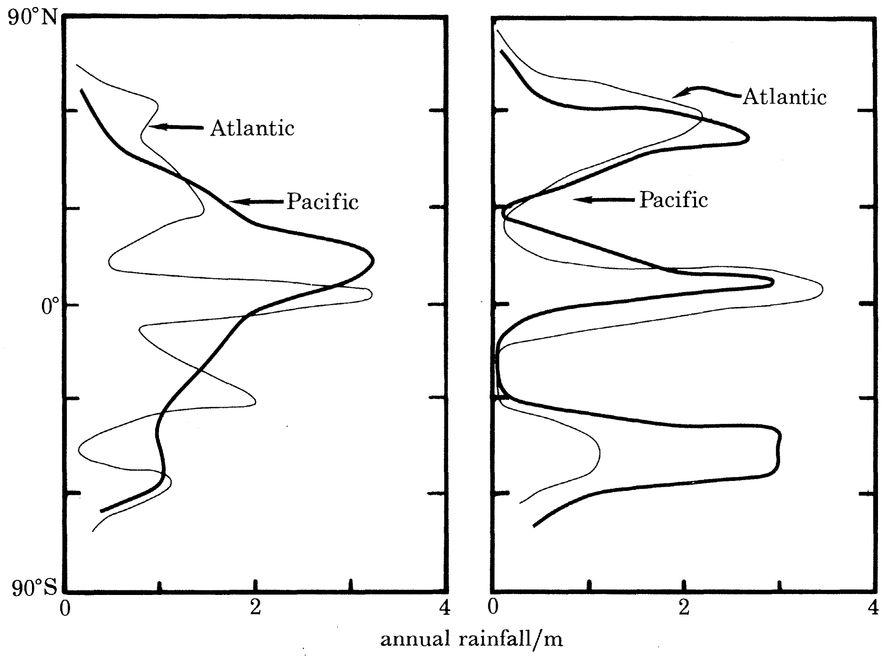

FIGURE 4. Annual precipitation along the western and eastern margins of the Atlantic and Pacific Oceans (from an unpublished world map prepared by T. T. Fujita, University of Chicago).

It is possible to go one step further and estimate the position of the successive margins of western South America from the Jurassic to the present. This we have done by assuming that the granodiorite intrusions through this interval have maintained the same distance from the inner trench wall as the modern calc-alkaline volcanoes (figure 3*b*). This distance in South America ranges from 250 to 400 km, with a well defined mean of 300 km. Some of the Jurassic plutons in northern Chile are presently within 50 km of the trench; this would imply that at least 200 km and more likely 250 km of the continental margin have been tectonically removed in a period of 200 Ma. This would mean that an average of about 12 cm of the width of western South America would be carried down the subduction zone during 100 years. Isotopic studies of modern volcanoes in this portion of South America suggest that the volcanic products are contaminated with up to 5% of continental material (Thorpe & Francis 1979). Perhaps tectonic erosion is the process by which continental crust is conveyed to the mantle for remelting.

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Our determination of the position of the continental margin in Colombia through time (figure 3*b*), based on intrusive foci, tends to be an overestimation when compared with the accreted wedges (figure 2*b*). Either the subduction zone was dipping more steeply in the past, as indeed it does in Panama today, or the accreted material was transferred around the top of South America by transcurrent faulting. In southern Chile, our method indicates removal of a segment of continental crust, and here the low angle of convergence of the Antarctic Plate and the geology suggest that the process responsible was transcurrent faulting.

We conclude that both plate tectonics and climate have combined to shape South America, and that the role of climate has been under-estimated in the past. Admittedly, South America is an extreme case; tectonic erosion on this scale must be a rare occurrence. The norm is for structural–magmatic patterns to migrate seaward, as they do on the opposite side of the Pacific (Zonenshain *et al.* 1974). Indeed, many Phanerozoic accretion zones are known (Ziegler *et al.* 1977). It is interesting to note that South American geologists would not agree about the normal direction of migration, to judge by the following quote from Aguirre (1976) 'The 'right' sequence of age in which the plutonic foci are located in northern and central Chile and also in Peru, i.e. from older to younger in a west to east direction and in a SW to NE direction in Peru, should be discussed in relation to the 'wrong' arrangement, a decrease in age from east to west in Colombia'.

Palaeozoic climatic effects

In this section we wish to test the dual assumptions that the Earth's present circulation patterns were operating during the Palaeozoic, and that the amount of rainfall has a pervasive effect on sediment type (Robinson 1973; Zeigler *et al.* 1979). We follow the lead of Briden (1968) in constructing pole-to-pole frequency plots to illustrate the palaeolatitudinal patterns of the major lithologic types for seven intervals of the Palaeozoic era.

At the present time, the Hadley circulation cells result in surface convergence and high rainfall at the equator and at the medium latitudes, while dry descending air characterizes the intervening subtropical belts and also the polar regions. The horizontal components of the wind complicates the matter somewhat. Along the eastern margins of oceans (figure 4), where the low-latitude horizontal wind component is from the east and is therefore off the land, conditions are especially dry. Along the western margins of oceans, the equatorial rainfall peak is very broad for the Pacific but the narrowness of the Atlantic results in the fact that areas in Venezuela and Brazil are within the 'shadows' of the Sahara and Kalahari deserts, respectively. At medium latitudes, the winds are dominantly from the west and therefore eastern shores receive a disproportionate amount of rainfall in this zone of convergence of temperate and polar air.

Despite these east–west asymmetries, it is true that the driest conditions occur in the subtropics centred about 20° north and south and ranging in some cases from 5 to 35° from the equator. This is where one would expect the Palaeozoic evaporites to occur. Clastics and coals should predominate in the equatorial rainy belt and these, together with tillites, should occur in the high precipitation zones centred at 45° north and south. In addition, we would expect carbonates to be restricted to the medium and low latitudes, and to predominate in the drier zones.

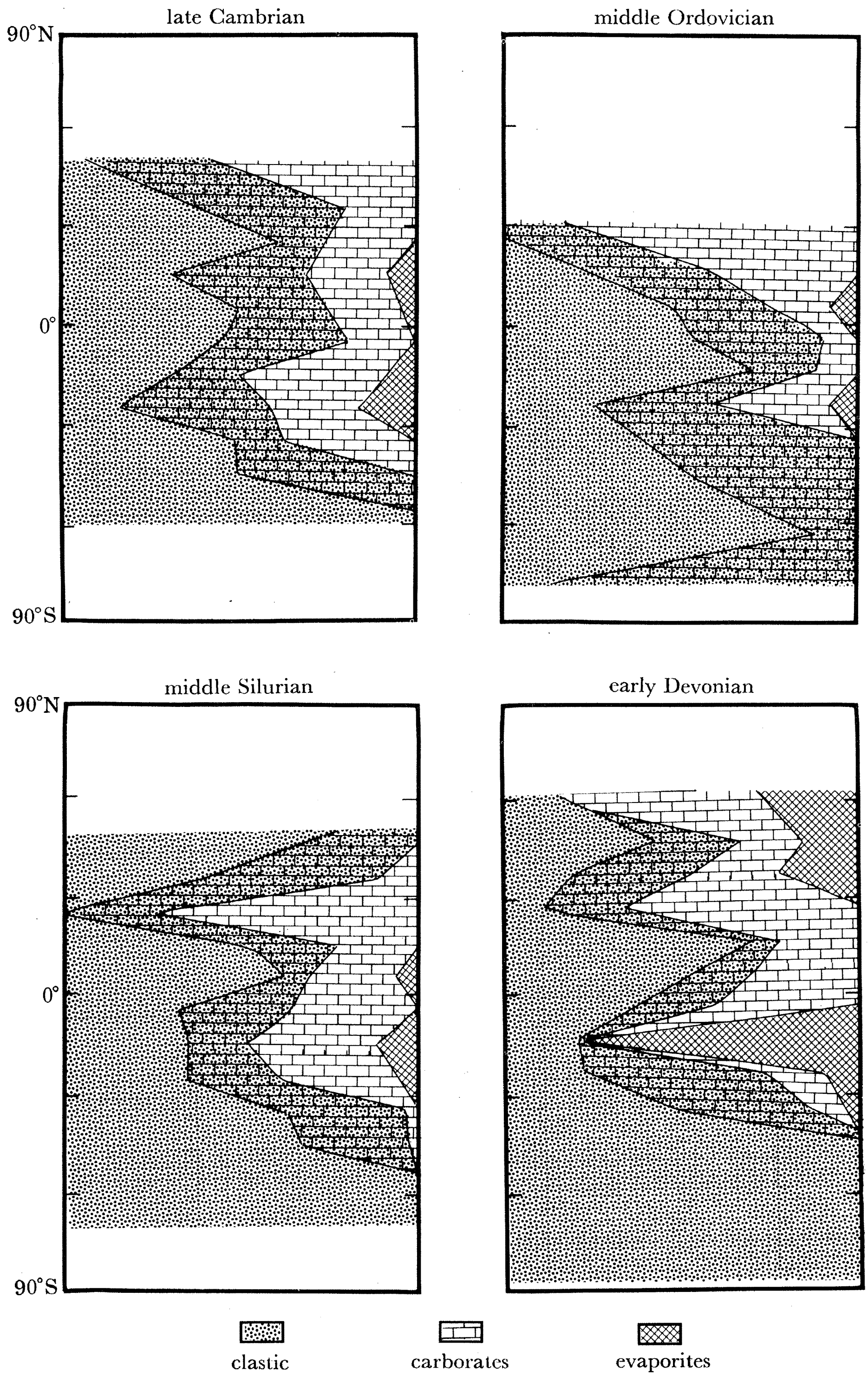

FIGURE 5. Pole-to-pole relative frequencies of the major sediment types for four intervals of the Lower to Middle Palaeozoic (data from Ziegler *et al.* (1979)).

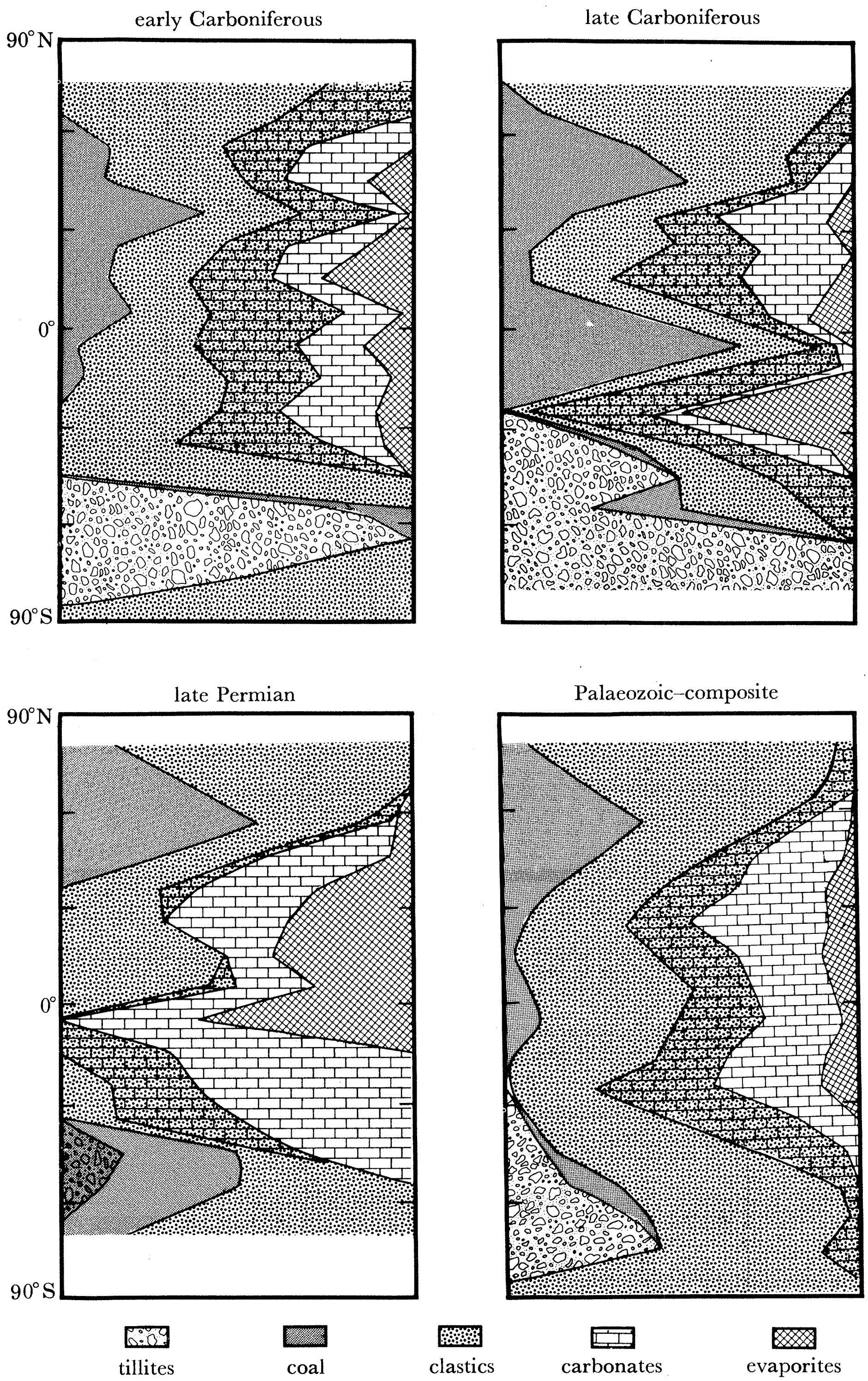

FIGURE 6. Pole-to-pole relative frequencies of the major sediment types for three intervals of the Upper Palaeozoic and for all intervals of the Palaeozoic combined (data from Ziegler *et al.* (1979)).

The Palaeozoic palaeolatitude plots for sediment type (figures 5, 6) were constructed from the data of Ziegler *et al.* (1979) and in general conform to the expectations presented above. The plots were constructed to facilitate comparison with the rainfall curves (figure 4); thus the wet climate indicators are shown on the left and their peaks should parallel the rainfall maxima. The effects of the equatorial rainy zone are marked by a strong peak on most of the plots for clastics and, in the Carboniferous, for coals as well as clastics. During periods in which there is strong asymmetry in the proportion of land in the northern as compared to the southern hemisphere, one would expect the equatorial peak to be drawn toward the land-dominated hemisphere. At present the intertropical convergence zone occurs about 5° north of the equator (figure 4). During the Palaeozoic, the Ordovician, Silurian and Devonian were periods of southern land dominance (Ziegler *et al.* 1979), though only our Ordovician plot (figure 5) gives any indication of a southward shift in the rainy zone.

The evaporites and carbonates generally show a bimodal pattern, with the peaks representing the two subtropical dry zones. The northern peaks on the Devonian and early Carboniferous occur further north than we would expect, but this may relate to errors in the palaeomagnetic predictions for Siberia. There is a tendency for the evaporite belts to occur closer to the equator in the early Palaeozoic than in the late Palaeozoic. This parallels a general increase in continentality, but could conceivably be due to the decrease in the Earth's rotation, which would have the effect of shifting the position of the subtropical high-pressure cells further from the equator through time (Ziegler *et al.* 1979).

The temperate rainy zones are well represented by clastics in the early Palaeozoic and by clastics and coals in the late Palaeozoic. In addition, tillites are manifest in the southern temperate and polar zones during the late Palaeozoic.

We conclude that the Palaeozoic lithofacies patterns reflect the balance of precipitation throughout the long interval. Also, we feel that the present Earth serves as a satisfactory model for precipitation patterns of the past. Before these relationships can be definitely established, more lithologic and palaeomagnetic data are required, as well as a more sensitive rendition of the orographic relationships. Work on this is in progress at the University of Chicago in the production of *An atlas of paleogeographic maps*.

We thank Leah Haworth, Carol Kazmer and Jean Pasdeloup for their technical and artistic endeavours. General support for our palaeogeographic research comes from the National Science Foundation (NSF grant EAR 7915133 to A.M.Z.), Shell Development Company, Amoco International Oil Company, Mobil Exploration and Producing Services Inc., Chevron Oil Field Research Company, Exxon Production Research Company, and the Exxon Education Foundation.

References (Ziegler *et al.*)

Aguirre, L. 1976 *Geol. Mag.* **113**, 475–485.
Aguirre, L., Charrier, R., Davidson, J., Mpodozis, A., Rivano, S., Thiele, R., Tidy, E., Vergara, M. & Vicente, J.-C. 1974 *Pacif. Geol.* **8**, 1–38.
Arango Calad, J. L., Kassem Bustamente, T. & Duque Caro, H. 1976 *Mapa geologico de Colombia* (1:1,500,000). Bogota: Instituto Nacional de Investigaciones Geologico-Mineras.
Barazangi, M. & Isacks, B. L. 1976 *Geology* **4**, 686–692.
Barrero-Lozano, D. 1979 *Publ. Geol. Esp. Ingeominas* **4**, 1–75.
Briden, J. C. 1968 In *The history of the Earth's crust, a symposium* (ed. R. A. Phinney), pp. 178–194. Princeton: Princeton University Press.

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Briden, J. C. 1970 In *Palaeogeophysics* (ed. S. K. Runcorn), pp. 437–444. London and New York: Academic Press.
Caelles, J. C., Clark, A. H., Farrar, E., McBride, S. L. & Quirt, S. 1971 *Econ. Geol.* **66**, 961–964.
Cobbing, E. J., Ozard, J. M. & Snelling, N. J. 1977 *Bull. geol. Soc. Am. Bull.* **88**, 241–246.
Dalmayrac, B., Lancelot, J. R. & Leyreloup, A. 1977 *Science, N.Y.* **198**, 49–51.
Dalziel, I. W. D., Dott Jr, R. H., Winn Jr, R. D. & Bruhn, R. L. 1975 *Bull. geol. Soc. Am.* **86**, 1034–1040.
de Almeida, F. F. M. (ed.) 1978 *Tectonic map of South America* (1:5,000,000). Dep. Nac. Prod. Min. (Brazil) and UNESCO.
DeWitt, M. J. 1977 *Tectonophysics* **37**, 53–81.
Drake, R. E. 1976 *J. Volc. geotherm. Res.* **1**, 265–284.
Drewry, G. E., Ramsay, A. T. S. & Smith, A. G. 1974 *J. Geol.* **82**, 531–553.
Evernden, J. F., Kriz, S. J. & Cherroni, M. C. 1977 *Econ. Geol.* **72**, 1042–1061.
Farrar, E., Clark, A. H., Haynes, S. J., Quirt, G. S., Conn, H. & Zentilli, M. 1970 *Earth planet. Sci. Lett.* **10**, 60–66.
Gansser, A. 1973 Facts and theories on the Andes. *J. geol. Soc. Lond.* **129**, 93–131.
Halpern, M. 1973 *Bull. geol. Soc. Am.* **84**, 2407–2422.
Halpern, M. 1978 *Bull. geol. Soc. Am.* **89**, 522–532.
Halpern, M. & Carlin, G. M. 1971 *Antarct. J. U.S.* **6**, 191–193.
Halpern, M. & Fuenzalida, R. 1978 *Earth planet. Sci. Lett.* **41**, 60–66.
Halpern, M. & Rex, D. C. 1972 *Bull. geol. Soc. Am.* **83**, 1881–1886.
Hayes, D. E. 1974 In *The geology of continental margins* (ed. C. A. Burk & C. L. Drake), pp. 581–598. New York: Springer-Verlag.
Helwig, J. 1972 *An. Acad. Brasil Cienc.* (*suppl.*) **44**, 161–171.
Henderson, W. G. 1979 *J. geol. Soc. Lond.* **136**, 367–378.
Herron, E. M. & Tucholke, B. E. 1976 In *Initial reports of the Deep Sea Drilling Project*, vol. 35 (ed. C. D. Hollister, C. Craddock *et al.*), pp. 263–278. Washington: U.S. Government Printing Office.
Herve, F., Munizaga, F., Godoy, E. & Aguirre, L. 1974 *Earth planet. Sci. Lett.* **23**, 261–264.
Hey, R., Johnson, G. L. & Lowrie, A. 1977 *Bull. geol. Soc. Am.* **88**, 1385–1403.
Irving, E. M. 1975 *Prof. Pap. U.S. geol. Surv.* no. 846.
Lefond, S. J. 1969 *Handbook of world salt resources*. New York: Plenum Press.
MacDonald, G. A. 1972 *Volcanoes*. Englewood Cliffs, New Jersey: Prentice-Hall.
McBride, S. L., Caelles, J. C., Clark, A. H. & Farrar, E. 1976 *Earth planet. Sci. Lett.* **29**, 373–383.
McNutt, R. H., Crocket, J. H., Clark, A. H., Caelles, J. C., Farrar, E., Haynes, S. J. & Zentilli, M. 1975 *Earth planet. Sci. Lett.* **27**, 305–313.
Minster, J. B. & Jordan, T. H. 1978 *J. geophys. Res.* **83**, 5331–5354.
Pitman, W. C., Larson, R. L. & Herron, E. M. 1974 *The age of the ocean basins*. Denver: Geological Society of America.
Plafker, G. 1972 *J. geophys. Res.* **77**, 901–925.
Robinson, P. L. 1973 In *Implications of continental drift to the earth sciences*, vol. 1 (ed. D. H. Tarling & S. K. Runcorn), pp. 451–476. London: Academic Press.
Shagam, R. 1972 *Mem. geol. Soc. Am.* no. 132.
Santamaria, F. & Schubert, C. 1974 *Bull. geol. Soc. Am.* **85**, 1085–1098.
Schmithusen, J. 1976 *Atlas zur biogeographie*. Mannheim: Bibliographisches Institut.
Smith, A. G. & Briden, J. C. 1977 *Mesozoic and Cenozoic paleocontinental maps*. Cambridge University Press.
Stewart, J. W., Evernden, J. F. & Snelling, N. J. 1974 *Bull. geol. Soc. Am.* **85**, 1107–1116.
Thorpe, R. S. & Francis, P. W. 1979 In *Origin of granite batholiths: geochemical evidence* (ed. M. P. Atherton & J. Tarney), pp. 65-75. Orpington: Shiva.
Wegener, A. 1966 *The origin of continents and oceans* (transl. J. Biram). New York: Dover.
Zeil, W. 1969 *Beiträge zur regionalen Geologie der Erde*, vol. 13. Berlin: Gebrüder Borntraeger.
Ziegler, A. M., Hansen, K. S., Johnson, M. E., Kelly, M. A., Scotese, C. R., & Van der Voo, R. 1977*a* *Tectonophysics* **40**, 13–51.
Ziegler, A. M., Scotese, C. R., McKerrow, W. S., Johnson, M. E. & Bambach, R. K. 1979 *A. Rev. Earth planet. Sci.* **7**, 473–502.
Zonenshain, L. P., Kuzmin, M. I., Kovalenko, V. I. & Saltykovsky, A. J. 1974 *Earth planet. Sci. Lett.* **22**, 96–109.

Discussion

B. W. Sellwood (*Department of Geology, The University, Whiteknights, Reading*). Professor Ziegler's climatic assumptions are based largely upon an Earth model with a modern aspect, with ice caps situated in polar areas and vigorous atmospheric régimes resulting from an intense heat differential between equatorial and polar areas. Consequences of the present régime are the Earth's relatively narrow and well defined climatic belts. While such a configuration of climatic belts is reasonably invoked for periods of Earth glaciation, somewhat less well defined and broader climatic zones may have been the rule for the long periods of time when polar regions were experiencing more equable climates than at the present. While I do not take issue with the generalities of climatically controlled facies zones (these ideas are long established in the literature), I do believe that some of the problems raised by Professor Ziegler (e.g. the northward and southward spread of carbonate and evaporite facies) may be explicable on non-uniformitarian climatic grounds rather than by subtle latitudinal shifts, as he suggests.

A. M. Ziegler. There is no question that the Earth's present climate is atypical of most past geological periods, particularly those with vast expanses of shallow seas. Nonetheless, there must always have been an equator-to-pole temperature differential, if one assumes that the Earth's rotational axis has not shifted drastically, and this temperature differential is the basic driving force of the Earth's circulation. In this paper we have stressed rainfall, and not temperature, as the primary control on world sedimentation patterns. We argue that rainfall belts have remained at relatively constant latitudes, while admitting that surface temperatures certainly have not.

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