The Paradox of Late Proterozoic Glaciations at Low Latitudes

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The aim of IGCP Project 260 (Earth's Glacial Record), which began in 1987, is to investigate the relationships between past glaciations and global climate and geodynamics. This article reviews the setting for one of the subprojects, which is concentrating on the conflict between paleomagnetic results and paleoclimate indicators for the Late Proterozoic. The topic for another subproject is the relationship between plate tectonics and glaciation, possibly in terms of the Wilson cycle, CO₂ de-gassing of the oceanic crust and paleoclimates. This is described briefly by G.M. Young in the box that follows. (Ed.)

Introduction

Lithologic and biologic indicators of climate define systematic, latitudinally distributed climatic zones on continental reconstructions for the Phanerozoic, suggesting that an analogous climatic zonation should also be possible for the Late Proterozoic. However, the distribution of warm-arid and glacial paleoclimatic indicators has been found to be highly irregular on a continental reconstruction for the latest Proterozoic (Vendian), and no global paleoclimatic zonation can be presently defined. The apparent lack of a climatic zonation would seem to indicate either that the paleoclimatic-paleomagnetic reconstruction and the low paleomagnetic inclinations are invalid, or that the distribution of paleoclimate indicators reflects significant changes in the Earth's climatic system during the Late Proterozoic.

The paradox of glaciations at low latitudes, inferred from paleomagnetic inclinations in Late Proterozoic strata containing glacial deposits, remains a major problem in geology. The paradox first arose from the early paleomagnetic studies of Harland and Bidgood (1959) and Bidgood and Harland (1961), supported by a number of later paleomagnetic studies (Runcorn, 1970; Piper, 1973; Tarling, 1974; Hambrey and Harland, 1981; Zhuhong, 1983). A widespread distribution of Late Proterozoic diamictite localities paralleling the low paleolatitudes inferred from paleomagnetic data appeared to support the paradox.

Several hypotheses were proposed in attempts to get around the problem. One supposes that the diamictites may be non-glacial (e.g. Volin, 1966; Klitin, 1965), though they may in places contain clasts derived from mountain glaciations (Schermerhorn, 1974, 1983). A second suggests that the glacial deposits accumulated on plates that moved through high and middle latitudes, with the low paleoinclinations superimposed after the fast-moving plates had entered low latitudes (Crowell, 1983). A third explanation holds that the diamictites are glacial and accumulated during global or near-global glaciations (e.g. Harland, 1964; Hambrey and Harland, 1985). In another hypothesis, Williams (1975) suggested that low-latitude glaciations were the result of an increased inclination of the Earth's axis of rotation with respect to the plane of the ecliptic. Finally, Sheldon (1984)

has proposed that the low-latitude glaciations were the result of shading of the Earth's equator by an icy ring similar to that of Saturn.

The first two hypotheses are difficult to support on geological and paleomagnetic grounds. The claim that the diamictites are not glacial has been undermined by studies that have shown that many (if not most) of the deposits that had been called diamictites are indeed glacial or glaciomarine in origin (e.g. Dow, 1965; Chumakov, 1968; Bessanova and Chumakov, 1969; Isotta et al., 1969; Spencer 1971; Zubtsov, 1972; Trompette, 1973; Young, 1970, and Deynoux, 1978). The Crowell hypothesis does not explain the generally low-latitude positions for cratons throughout most of Middle and Late Proterozoic time, regardless of the presence or absence of diamictites in the sections, and it does not account for a lack of relict magnetizations (arising from incomplete overprinting) that would record the postulated excursions into high latitude positions at the times of glaciation. In order to evaluate the other three hypotheses, which all accept the low-latitude positions of the glaciations, we briefly review some paleoclimate data.

Figure 1: Distribution of climatic indicators for Vendian time (560-680 Ma) plotted on plate reconstruction of Khramov (1983, Fig. 1a) for the Vendian System. Explanation: 1 - continental glacial deposits; 2 - mainly marine glacial deposits; 3 - direction of ice movement; 4 - seasonal ice deposits; 5 - diamictites of possible Vendian age; 6 - evaporites; 7 - thick section of dolomite; 8 - thick section of limestone; 9 - limy red beds; A - Africa; An - Antarctica; Au - Australia; E - Europe; I - India; NA - North America; SA - South America; S - Siberia.

Climate Indicators and Zones

The principal climatic zones today consist of tropical arid zones flanking a humid equatorial zone. The arid zones, in turn, are flanked by wetter and cooler climatic zones, and these give way to the glacial regimes of the polar regions. These strongly contrasting climatic zones appear to have been present during intervals of Phanerozoic glaciation (e.g., Early Permian and Pleistocene; Chumakov, 1985, 1986). During non-glacial periods, warm extra-tropical and warm-temperate climates occurred at middle and high latitudes (e.g. during the early Paleozoic, Mesozoic, and early Cenozoic; see Chumakov, 1985).

The latitudinal distribution of the climate zones is apparent in paleomagnetically controlled plate reconstructions for the Paleozoic. However, at least one anomaly exists. In a reconstruction for Early Carboniferous time the equatorial climatic zone is tilted in a distinct northwesterly sense across North America with respect to the equator (Chumakov, *ibid.*). Nonetheless, paleolatitude spectra for the Phanerozoic indicate that glacial and seasonal ice deposits accumulated no closer to the equator than 30° latitude, and that evaporite deposits and biogenic reefs accumulated no farther from the equator than 35° to 50°.

An attempt then was made to apply the same paleoclimatic approach to the Late Proterozoic (Fig. 1). Deposits of the Vendian System (Sokolov et al., 1985) ranging from about 650 to 560 Ma old were chosen to represent the best-studied interval of latest Precambrian rocks. Lithologic indicators of climate from these rocks were derived from several sources (Vinogradov, 1967; Keller et al., 1974; Stocklin, 1968; Semikhatov, 1974; Khomentovskiy, 1976; Khain et al., 1981; Ronov et al., 1981; Young, 1981; Preiss, 1987). The climate indicators then were plotted with respect to a paleomagnetic plate reconstruction of Khramov (1983, fig. 1a). A reconstruction for this interval by Piper (1982) is similar to that of Khramov, and reconstructions by Morel and Irving (1978), Osipova (1981), Monin and colleagues (1986), and others show similar paleolatitudinal positions for the continents.

No regularities in the distribution of climate indicators and no climatic zonations are recognized for the Vendian (Fig. 1). Climate indicators that record warm-arid conditions (evaporites, carbonates, limy terrigenous red beds) are in proximity to and at the same latitudes as glacial deposits. In general, the indicators of climate for the Vendian have irregular, spotty distributions, and some glacial deposits appear to be flanked in space by evaporites (e.g., compare Europe-Greenland with Siberia on Figure 1). The paleolatitude spectra of the glacial and evaporite deposits on Figure 1 are similar, ranging from +10° to -62° and 0° to -60°, respectively. These Vendian distributions differ markedly from those in the Phanerozoic and appear abnormal with respect to the distribution expected for deposits that reflect glacial and warm-arid conditions. In view of this, the paradox of low-latitude glaciation in the Late Proterozoic perhaps can be regarded as part of a more general paleoclimatic paradox.

The problem might be assumed to result from a failure of the plate reconstruction shown in Figure 1 arising from invalid paleomagnetic data, or the paradox might be attributed, partly or wholly, to dramatic changes in the

Figure 2: Distribution of principal glacial episodes during past 1000 Ma (from Chumakov, 1986).
Explanation: Q-N₂, N₁, P₃ - late Cenozoic; P₂ - Late Permian; P₁, C₃ - Early Permian and late Carboniferous; C₂, C₁? - middle and early Carboniferous; D₃ - Devonian; S₁, O₃ - Early Silurian and Late Ordovician; V₂ - late Venidian; V₁ - early Venidian; R₃ - late Riphean, ²-late, ¹-early.

Earth's climatic system. In the latter case, the times of change presumably would include not only three potentially discrete Vendian glaciations but also two older late Riphean glaciations (Fig. 2).

The apparently abnormal distribution of climatic indicators cannot be explained by any of the five general hypotheses listed previously. Moreover, the explanation involving increased inclination of the Earth's rotation axis appears not to be valid for three different reasons. First, it does not explain the wide distribution in latitude (0°-60°) of the glacial and evaporite deposits (Fig. 1). Second, an increase in inclination of the Earth's axis of rotation is a feature to be expected in the distant future rather than in the geologic past (Hunt, 1979; Monin and Sishkov, 1979). Third, convective heat transfer by the Earth's atmosphere and ocean circulation appears to have generally compensated for the large negative radiation balance of high-latitude parts of the globe during the non-glacial parts of the Phanerozoic. The circulations also should have been adequate to dampen a lesser seasonal radiation balance of low latitudes in the case of a high angle inclination of the Earth's axis of rotation.

Sheldon's (1984) hypothesis that the equatorial region was shaded by an icy ring does not accord with the low-latitude distribution of some of the evaporites, or with the middle-latitude distribution of some of the glacial deposits. Lastly, a hypothesis calling for global or sub-global glaciations does not accord with the wide distribution in paleolatitude of the Vendian evaporites and the regional limitations of the

GLACIATION AND TECTONICS

Part of the mandate of IGCP Project 260, "Earth's Glacial Record," is to investigate possible relationships between glaciation and tectonics. During the early history of the Earth, according to astronomical theory, solar luminosity, should have been about 25% less than at present. It is therefore puzzling that there are so few well documented examples of glacial rocks in the Archean. Possibly the primitive Earth was enveloped in an atmosphere rich in greenhouse gases, so that even the weakly radiative sun produced sufficient heat to prevent widespread glaciation.

Glaciation is manifested in both the Early and Late Proterozoic, but there is a long time interval, between about 2.0 Ga and 1.0 Ga ago, when there is no record of glaciation on Earth. The absence of glacial deposits over such a long time span is perhaps more puzzling than its occurrence in the preceding and subsequent parts of the Proterozoic record.

Figure A is an attempt to represent schematically the stratigraphic (and inferred plate tectonic) setting of Early Proterozoic rocks of North America. This generalized reconstruction is based on the Huronian Supergroup of Ontario, the Snowy Pass Supergroup in Wyoming and the Hurwitz Group in the Northwest Territories. The critical feature is the preservation of glacial rocks in what are interpreted as the rift and rift-drift transition phases. In the southern hemisphere, Early Proterozoic glacial rocks are best known from South Africa and Western Australia. The stratigraphic context is well documented, but the plate tectonic setting is at best speculative. In Figure B it is tentatively suggested that these local glacial deposits could be related to the closing phases of a Wilson cycle. Iron-formations in the Early Proterozoic formed in siliclastic-starved basins and may have been largely hydrogenous.

Figure A: Schematic representation of inferred plate tectonic setting of glacial rocks (triangles and letter "T" indicate glacial deposits) in Early Proterozoic successions of the northern hemisphere. Arrows represent major sediment transport directions. Note that evidence of glaciation is preserved in the rift phase and at the rift-drift transition. Iron-formation (BIF) occurs near the base of the foreland basin flysch.

Late Proterozoic glacial deposits are known from all continents. Most of these rocks are preserved in what are interpreted as rift basins, precursors to the break-up of a Late Proterozoic supercontinent. Intimately associated iron-formations are probably related to hydrothermal exhalations accompanying the rifting process.

Recent studies of Phanerozoic glacial deposits and paleoclimates in general have led to the suggestion that climatic change on Earth over the last 600 Ma is related primarily to fluctuations in the CO_2 content of the atmosphere. These changes, in contrast to the recent industrial atmospheric pollution, are related to plate tectonic processes. Cold periods ("icehouse effect") appear to be linked to two plate tectonic configurations: one related to the existence of a high-standing supercontinent and the other to periods, like the present, when an expanding Atlantic-type ocean approached its maximum extent leading to a high percentage of "old," dense oceanic crust that sinks and causes lowering of relative sea level. Under both conditions, the continents are high standing. Most of the Early and Late Proterozoic glacial occurrences probably fall into the first category whereas the Pleistocene glaciation would be of the second type.

	Early Proterozoic		Late Prot
	N. Hemisphere	S Hemisphere	Global
RIFT			HYDROTHERMAL ACTIVITY
MIOCLINE	CLASTIC	CHEMICAL	
FOREDEEP	CLASTIC	CLASTIC	
	much dissolved Fe in oceans		little Fe

Figure B: Summary diagram to illustrate the inferred plate tectonic setting of Early and Late Proterozoic glacial rocks (shown by cross hatching) and iron-formations (shown by thick black bars). Note that glacial rocks (and iron-formations) are interpreted to occur in different settings in the northern and southern hemispheres. Late Proterozoic glacial rocks and iron-formations are interpreted as rift-related deposits.

The link between plate tectonics and CO_2 content of the atmosphere (and hence paleoclimate) seems at first obscure, but computer modeling has revealed that the most important factor in controlling atmospheric CO_2 levels is the rate of degassing. A second important factor is the rate of weathering of continental crust, which increases during periods of low sea level. Degassing would be minimized, and continental weathering maximized during both conditions described above. Because of the marine transgressions that typically follow continental fragmentation the deposits of type "a" glaciations should be preferentially preserved in the geologic record, and it is to this condition that most of the Proterozoic occurrences are ascribed.

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Figure 3: Paleolatitudes for interval 1,250-250 Ma for several continents and subcontinents. Sources for data points. **North America** - Proterozoic rocks: Middle Proterozoic Belt Supergroup, Montana and Idaho, and Middle and Late Proterozoic Grand Canyon Supergroup, northern Arizona, western U.S. (from Elston and Bressler, 1980, and in review; Elston and Grommé, 1975, 1979, 1984, and in review; and Elston, 1984, 1986, 1988a). Middle Proterozoic upper Keweenaw Jacobsville Sandstone of Keweenaw Peninsula, northern Michigan (Roy and Robertson, 1978); and upper Keweenaw Chequamegon Sandstone of northern Michigan, (McCabe and Van der Voo, 1983). Late Proterozoic Uinta Mountain Group, Utah and Colorado (Bressler, 1981). Late Proterozoic Little Dal Group, Mackenzie Mountains, northwest Canada (Park, 1981a); and ~770-Ma sills in Tsezotene Formation beneath Little Dal Group (Park, 1981b; Armstrong and others, 1982; Park and Aiken, 1986). Z component of magnetization in glaciogenic Late Proterozoic Rapitan Group, Windermere Supergroup, western Canada (Morris, 1977). Late Proterozoic Franklin intrusions (~600-650 Ma), northern Canada (Palmer and Hayatsu, 1975). Paleozoic strata: Poles and provisional polar path for Cambrian to Permian rocks including Lower to Middle Cambrian Tapeats Sandstone, and Middle Cambrian Bright Angel Shale, Grand Canyon (Elston and Bressler, 1977, 1984; Elston, 1988b); Silurian Rose Hill, Hersey, and Wabash Formations, eastern and central U.S.A. (French and Van der Voo, 1979; Kent and Opdyke,

1980; McCabe and others, 1985); Devonian Maywood Formation, western Montana (Elston and Bressler, 1984; Elston 1988b); Carboniferous strata of New Brunswick (Roy and Robertson, 1968; Roy and Park, 1969, 1974; Roy, 1977); preliminary pole from Pennsylvanian strata of Supai Group, Marble Canyon (D.P. Elston, unpublished data); pole from six sites in Lower Permian strata of Supai Group of northern and central Arizona (Chino Point (Steiner, 1988) and Sedona (Elston, 1988b), and Lower Permian Abo Formation of New Mexico (Steiner, 1988)); Late(?) Permian overprint pole on Cambrian and Devonian strata, northern and central Arizona (Elston, 1988b); Lower and Middle(?) Triassic Moenkopi Formation, northern Arizona (Purucker and others, 1980). **West Africa** (Mauritania), Perrin and others (1988); **North China** (Jixian section); Elston and others, (1989); **South China** (Changhe section), Zhang and others, (1989); **Fennoscandia**, L.J. Pesonen, (written communication, 1988). The southerly high-latitude shift of the pole for R950 Ma for Fennoscandia also is seen in a polar path proposed from the crystalline Grenville Province of North America (e.g. Berger and others, 1979; Dallmeyer and Sutter, 1980). This southerly shift is not seen in poles from the tilt-corrected stratified rocks of the western cordillera, and therefore has not been shown on the plot of paleoinclinations for North America. Note also that the paleolatitude of Fennoscandia for the Vendian assumes an opposite polarity from that used for the reconstruction in Figure 1.

individual, discrete Vendian glacial deposits (Chumakov, 1978; Hambrey and Harland, 1985; Sokolov et al., 1985). Unfortunately, the close temporal control needed to evaluate the contemporaneity of individual glacial and warm periods on a global scale for the Vendian still is lacking, an uncertainty that also exists for an Ordovician-Silurian reconstruction (Chumakov, 1985).

Paleomagnetic Paleolatitudes

Paleomagnetic studies continue to reinforce the earlier conclusion that many Late Proterozoic sequences on different continents accumulated at low paleolatitudes. As displayed on Figure 3, paleolatitudes for the cratonic areas shown remained generally low throughout the Middle and Late Proterozoic and for much of Paleozoic time. Paleolatitudes inferred from the low inclinations provide no evidence to support excursions of the plates from low to moderate or high latitudes that might correlate with one or more episodes of Late Proterozoic glaciation. If the paleomagnetic data shown on Figure 3 are accepted at face value, glacial deposits contained in the Late Proterozoic sequences accumulated at low latitudes.

It is true that glacial deposits in the Late Proterozoic sections generally do not contain stable remanent magnetizations and that their low paleolatitudes are inferred from low inclinations in strata that enclose or are broadly correlative with the glacial deposits. Nonetheless, the directions of remanent magnetization from the enclosing or correlative strata have been determined following appropriate and extensive thermal and alternating-field cleaning, and have been calculated from clusters of sample and site directions lacking "streaks" that would reflect unremoved components of secondary magnetization. In some cases, the paleomagnetic directions are supported by antiparallel reversals, indicative of a lack of significant secondary magnetizations. In other cases, the low paleomagnetic inclinations have come from igneous rocks, so *ad hoc* appeals to unrecognized secondary magnetizations residing in certain rock types (e.g. red beds) also appear not to be valid.

Thus, no evidence is recognized that supports the proposal that low inclinations are the consequence of secondary overprinting following movement of plates from high or moderate latitudes into lower latitude positions. Remnants of "pre-overprint," higher latitude inclinations should have been detected if the plates had undergone rapid movement, first toward and then away from the pole to produce the contained glaciations at high or even middle latitudes.

Summary

The problem of the paradox of low-latitude glaciations during the Late Proterozoic remains unresolved, but the problem now can be regarded as part of a more general paradox. Two potential causes for the paradox are that either the paleomagnetic reconstructions and paleolatitudes (Khain and Yasamanov, 1987) or the paleoclimatic reconstructions are incorrect. However, creditable scenarios allowing the paleomagnetic or paleoclimatic data sets to be discarded do not appear to exist.

If the irregular distribution of climate indicators and the apparent lack of a climatic zonation during the Late Proterozoic is real, multiple and dramatic changes in the Earth's climate system can be inferred to have occurred during the Late Proterozoic. Rejection of paleolatitudes derived from inclination data is a much more difficult proposition than the rejection of any particular continental reconstruction based on pole positions. We also note that if glacial deposits were not present in the Late Proterozoic sections, no reason would exist to question the validity of the low paleomagnetic inclinations and the generally low paleolatitudes of accumulation.

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