Implications of ash dispersal for tectonic models with an example from Wopmay orogen

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ABSTRACT

The Coronation Supergroup, a 1.9 Ga west-facing, continental-margin prism in the Wopmay orogen, represents the opening and closing of a basin; but was this an open ocean or a back-arc basin? The ≈10 m.y. life span of the basin suggests a Korean-type margin, but geological arguments have been raised against a back-arc interpretation. The most serious argument is the lack of ash beds in lagoonal facies of the shelf despite prevailing onshore winds. On the basis of combined paleomagnetic data, stromatolite elongation, starved foreslope, and other sedimentological evidence, the margin faced east and deposition occurred in the belt of trade winds at lat 10°–20°N. However, ash is generally not distributed by low-level winds, such as trades, but by winds in the troposphere; ash erupted from an offshore arc located near lat 15°N would probably have been transported away from the margin, not toward it. This nullifies the strongest geological argument against a back-arc origin for the Coronation Supergroup, which is supported by many independent lines of evidence. The method described has potential for determining whether other ancient basins represent back-arc basin fill or continental-margin deposits of an open ocean.

INTRODUCTION

In many ancient orogenic belts the question of whether a thrust-fold belt represents a collapsed back-arc basin or an arc-continent collision is critical for a proper understanding of the tectonic evolution of the orogen. Criteria based on sedimentary facies, volcanic geochemistry, and structural style are often ambiguous, and other methods for recognition must be found. In some cases, windborne volcanic ash (Eaton, 1964), injected into the troposphere by Plinian eruptions and deposited hundreds of kilometres from the volcano, may be used to test different models. The example used here is located in the Wopmay orogen.

The Coronation Supergroup of the Wopmay orogen is a widely cited example of an Early Proterozoic continental-margin prism (Hoffman, 1973), but whether it represents an Atlantic- or Korean-type (back-arc) margin is equivocal. Hoffman and Bowring (1984) presented geochronological evidence that the basin was open for only ≈10 m.y., which would appear to favor the back-arc alternative. However, they raised geological objections to this interpretation and so favored a short-lived Atlantic-type margin. The purpose of this paper is to reassess the geological arguments used to exclude the back-arc model and by doing so demonstrate how the dispersal of windborne volcanic ash can assist in resolving tectonic problems.

CORONATION SUPERGROUP

The 1.9 Ga Wopmay orogen, located on the western side of Slave craton in the northwestern Canadian Shield, includes a succession of rocks collectively known as the Coronation Supergroup (Hoffman, 1973). The supergroup contains a ternate stratigraphy: a lower rift-facies clastic-volcanic assemblage (Akaitcho Group); a middle passive-margin sequence (Epworth Group) comprising a siliciclastic blanket (Odjick Formation) and an overlying carbonate terrace (Rocknest Formation); and an upper foredeep succession (Recluse Group). Rocks of the supergroup are interpreted to record the opening and closing of a short-lived, west-facing, passive continental margin (Hoffman and Bowring, 1984). U-Pb zircon geochronology (Hoffman and Bowring, 1984) suggests that the period of time for the evolution of the margin (≈10 m.y.) was shorter than comparable Phanerozoic margins, and they postulated that this might be a consequence of faster oceanic plate recycling in the Proterozoic as compared with the Phanerozoic. Although they conceded that the tectonic setting of the initial rifts is poorly known, they listed three objections to the back-arc model: "(1) compositions of lavas and clastic detritus in the Akaitcho Group, which do not resemble products of a rifted arc (Easton, 1982, p. 307–308); (2) absence of (arc-derived) volcanic ash anywhere above the base of the Epworth shelf, despite prevailing onshore winds (Hoffman et al., 1983); and (3) lack of arc-derived detritus in the (extremely immature) turbidites of the foredeep" (Hoffman and Bowring, 1984, p. 69). Regarding objection 1, basalts from the Akaitcho Group (Easton, 1982) have geochemical characteristics well within the range of modern marginal basin basalts (Tarney et al., 1981). In addition, if rifting occurred behind rather than within the arc, it would not be surprising, considering the difficulty of transporting debris from one side of a rift domain to the other, that sedimentary rocks of the group reflect a local source (i.e., continental side of the basin). Furthermore, individual Akaitcho allochthons, perhaps derived from separate fault-bounded subbasins (Hoffman and Pelletier, 1982), are known to have different detrital suites (Bowring, 1984). The lack of arc detritus in the foredeep is equivocal because the turbidites of the foredeep were transported axially from an unknown source to the north. Perhaps the most compelling objection (Hoffman and Bowring, 1984) was the lack of ash horizons in the quiescent, red lagoonal lutites of the Rocknest Formation (Grotzinger, 1986a, 1986b), notwithstanding evidence for prevailing onshore winds at sea level. I will demonstrate here that this argument is flawed because volcanic ash is typically ejected to high atmospheric levels where it is transported and dispersed by tropospheric winds rather than trade winds or other low-level phenomena.

PALEOWINDS

It is necessary to recap the reasoning that led to the conclusion that there were onshore winds during deposition of the sediments. Hoffman et al. (1983) noted that elongate stromatolites in the reef and back-reef facies of the Rocknest Formation, which has a north-trending shelf edge, are oriented northeast-southwest (N20°–40°E) even where not tectonically strained (P. Hoffman, unpub. data). They suggested that the most tenable explanation for the elongation is that it reflects the dominant paleowind direction (southwest-northeast). Prevailing onshore winds are indicated by the starved nature of foreslope facies in the Rocknest Formation (Grotzinger and Hoffman, 1983; Grotzinger, 1986a, 1986b, 1986c) and by the combination of westerly paleocurrents and storm-generated sedimentary structures in the shallow-marine Odjick Formation, which suggest deposition by storm-surge ebb currents formed by the return of water driven against the shoreline by predominant onshore winds (Hoffman et al., 1984). Thus, three lines of evidence taken together point to prevailing oblique onshore winds from the southwest (present coordinates) during deposition of the Epworth Group.

GLOBAL POLARITY

Paleolatitudes (Evans and Hoye, 1981) for sequences correlated with units stratigraphically above and below the Rocknest Formation are

16°–17° and 10°, respectively, indicating that the stromatolites formed in the near equatorial regions (≈15°) dominated by trade winds. However, the polarity (whether they were deposited in the Northern or Southern Hemisphere) is equivocal due to limitations inherent in the paleomagnetic method. Hoffman et al. (1983) noted that if the paleowind interpretation is correct, then the ambiguity regarding polarity can be settled because the trade winds do not blow directly from the east between lat 10° and 20° but, rather, from the northeast and southeast in the Northern and Southern Hemispheres, respectively (Fig. 1). Because the paleopoles for the Coronation Supergroup plot in northern South America (Irving and McGlynn, 1979), there are only two possible configurations for the region at that time (Fig. 1). It is clear that if the paleowind interpretation is correct, only the Northern Hemisphere model is tenable. The trade winds would have blown from an offshore volcanic arc across the basin toward the Slave craton, as inferred by Hoffman and Bowring (1984).

ASH DISPERSAL

The critical factor is how volcanic ash is dispersed. During a volcanic eruption, hot gases and pyroclasts are propelled into the atmosphere, and the resultant eruption column rises, mainly due to thermal buoyancy, until it reaches the same density as its surroundings, where it begins to spread out (Wilson et al., 1978; Sparks, 1986). Large eruption plumes, such as formed by Plinian and ultra-Plinian eruptions, rise to heights of 10–40 km (Jakosky, 1986), where they are transported laterally by the prevailing high-level winds. Most distal ash beds result from ash transported by tropospheric rather than stratospheric winds (Sigurdsson and Carey, 1981). This reflects the inability of all but the smallest size ($<4\ \mu$m) particles to rise above the tropopause due to gravity and air-drag forces (Settle, 1978), the extremely long settling times and broad dispersal index for such tiny particles (Pollack et al., 1976; Walker, 1981), the strong temperature inversion at the tropopause (Defant and Taba, 1957), and the infrequent occurrence of very large eruptions (Volcanic Explosivity Index [VEI] >4; Simkin et al., 1981). Although the azimuth of high-level wind varies considerably as functions of season, location, and height, there is a well-developed semipermanent westerly jet stream in the troposphere of subtropical regions (Palmén and Newton, 1969). Therefore, transport of ash produced in those areas during explosive to paroxysmal eruptions (VEI >2) is predominantly from west to east.

A well-documented modern example of ash dispersal by tropospheric winds occurs in the Lesser Antilles, which constitute an active volcanic arc situated in the belt of trade winds north of the equator at the same latitudes as proposed for the Wopmay orogen during the Early Proterozoic. There, Quaternary ash layers occur almost exclusively on the Atlantic side of the arc, despite northeasterly trades and oscillatory stratospheric winds (Sigurdsson et al., 1980). This is because the trade winds give way to high-velocity westerlies above the 5 to 8 km level and because little ash rises above the tropopause (Sigurdsson and Carey, 1981).

IMPLICATIONS

If the orientation of the stromatolites in the Rocknest Formation reflected paleowind direction, and if the area were located in the trade-wind belt of the Northern Hemisphere, then ash dispersal would probably have been away from the Slave craton, not toward it, because tropospheric winds are westerly and blow offshore. This removes the most potent objection of Hoffman and Bowring (1984) to the possibility that the Coronation Supergroup was deposited on a Korean-type margin flanking an evolving back-arc basin. Such an interpretation is consistent with several features not adequately explained by the Atlantic-type model: (1) the greenschist facies metamorphism in the foreland (Lucas, 1984; Hoffman et al., 1988); (2) the occurrence of mafic flows and sills in the shelf facies of the lower Odjick Formation (St-Onge et al., 1982); (3) the swarm of mafic sills emplaced into orogenic flysch at the Rocknest shelf edge (foredeep magmatism of Hoffman, 1987); (4) the intrusion of the arc-related Hepburn batholith into the basinal facies of the Coronation Supergroup (Lalonde, 1986); and (5) the thermal evolution of the basin (St-Onge and King, 1987a, 1987b). Furthermore, recent geochronological and geologic data from the extreme western part of the orogen (Reichenbach, 1986a, 1986b) independently support the back-arc model.

The Kilohigok basin, located on the eastern side of the Slave craton opposite the Wopmay orogen, is an Early Proterozoic foredeep basin that developed in response to loading of the Slave craton by the northwest Rae craton during continent-continent collision (Hoffman, 1988). The basin contains a carbonate platform in which bioherms and individual stromatolites are oriented north-northeast (Campbell and Cecile, 1981; Pelechaty and Grotzinger, 1988) oblique to the trend of the syndepositional flexural arch that trends northeast (Grotzinger et al., 1988). Although the basin is located hundreds of kilometres from the Wopmay orogen and is on the other side of the craton, the stromatolite orientation is the same. The orientation is consistent with a paleowind control on stromatolite orientation, but because the margin faces southeast, tropospheric winds would have been crudely onshore and the Kilohigok basin might contain abundant ash beds deposited by winds traveling toward the basin from an arc on the Rae craton. Recent work by Grotzinger (1987, personal commun.) has demonstrated numerous ash beds within the Kilohigok basin.

The method used here has the potential to clarify the tectonic setting of other problematic thrust-fold belts, in that the question of whether an ancient thrust-fold belt formed in a back-arc or fore-arc setting is often ambiguous because of the similarities in structural style, volcanic geochemistry, and sedimentary facies between the two environments. Careful analysis of paleomagnetic data combined with knowledge of ash dispersed during Plinian eruptions might resolve this problem. For example, Laurentia appears to have been within 30° of the equator from the Cambrian to the Permian (Scotese, 1984), and interpretation of problematic plate-microplate-arc interactions, such as recorded by the Ordovician-Silurian volcanic rocks of the Dunnage and Gander zones in the northern Appa-

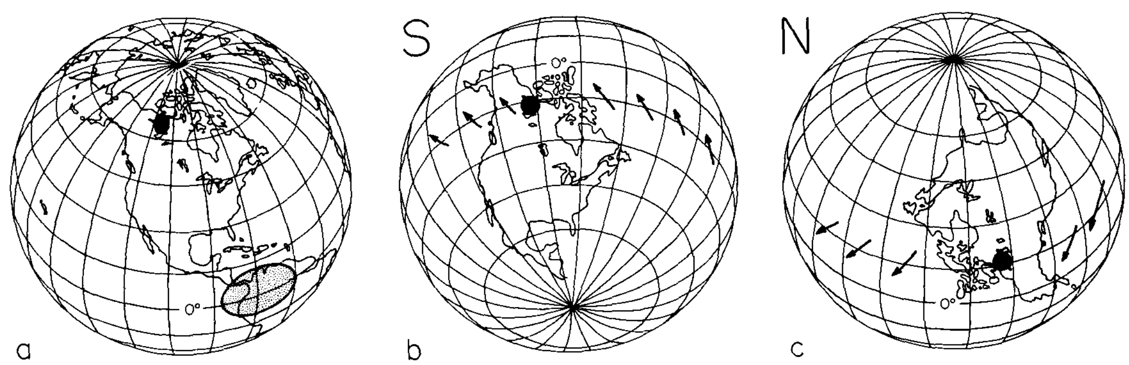

Figure 1. a: Sketch map of Western Hemisphere showing present location of Wopmay orogen (solid oval) and its paleopole (stippled oval). b: Configuration of Wopmay orogen relative to trade winds in the Southern Hemisphere model (North America for reference). c: Northern Hemisphere model. Note that trade winds blow nearly orthogonal to stromatolite orientation in b, but parallel to it in c. Paleopole from Irving and McGlynn (1979); trade-wind directions are from Hasse and Dobson (1986).

lachians during the Alleghenian orogeny (van Staal, 1987) and the Permian McCleod-Cache Creek belts of the North American Cordillera (Miller, 1987), might be facilitated by examining proximate sedimentary sequences on the adjacent craton for the presence or absence of ash beds. Where a shelf sequence contains just a few ash beds, the shape of individual particles should be examined if possible because in rare cases ash that formed during ignimbrite eruptions may be deposited over great distances by low-level winds (Rose and Chesner, 1987).

REFERENCES CITED

Bowring, S.A., 1984, U-Pb zircon geochronology of Early Proterozoic Wopmay orogen, N.W.T., Canada: An example of rapid crustal evolution [Ph.D. thesis]: Lawrence, University of Kansas, 148 p.

Campbell, F.H.A., and Cecile, M.P., 1981, Evolution of the Early Proterozoic Kilohigok basin, Bathurst Inlet–Victoria Island, Northwest Territories, *in* Campbell, F.H.A., ed., Proterozoic basins of Canada: Geological Survey of Canada Paper 81-10, p. 103–131.

Defant, F., and Taba, H., 1957, The threefold structure of the atmosphre and the characteristics of the tropopause: Tellus, v. 9, p. 259–274.

Easton, R.M., 1982, Tectonic significance of the Akaitcho Group, Wopmay orogen, Northwest Territories [Ph.D. thesis]: St. John's, Memorial University of Newfoundland, 432 p.

Eaton, G.P., 1964, Windborne volcanic ash; a possible index to polar wandering: Journal of Geology, v. 72, p. 1–35.

Evans, M.E., and Hoye, G.S., 1981, Paleomagnetic results from the lower Proterozoic rocks of Great Slave Lake and Bathurst Inlet areas, Northwest Territories, *in* Campbell, F.H.A., ed., Proterozoic basins of Canada: Geological Survey of Canada Paper 81-10, p. 191–202.

Grotzinger, J.P., 1986a, Measured stratigraphic sections and palinspastic cross-sections, Rocknest Formation (1.9 Ga), Wopmay orogen, Northwest Territories: Geological Survey of Canada Open File 1278.

——1986b, Evolution of an Early Proterozoic passive margin carbonate platform, Rocknest Formation, Wopmay orogen, Northwest Territories, Canada: Journal of Sedimentary Petrology, v. 56, p. 831–847.

——1986c, Cyclicity and paleoenvironmental dynamics, Rocknest platform, northwest Canada: Geological Society of America Bulletin, v. 97, p. 1208–1231.

Grotzinger, J.P., and Hoffman, P.F., 1983, Quantitative paleobathymetry of Early Proterozoic (1.9 b.y.) continental slope, Rocknest Formation, Wopmay orogen, N.W.T., Canada [abs.]: American Association of Petroleum Geologists Bulletin, v. 67, p. 475.

Grotzinger, J.P., Gambia, C., Pelechaty, S.M., and McCormick, D.S., 1988, Stratigraphy of a 1.9 Ga foreland basin shelf-to-slope transition: Bear Creek Group, Tinney Hills area of Kilohigok basin, District of Mackenzie, *in* Current research, Part C: Geological Survey of Canada Paper 88-1C, p. 313–320.

Hasse, L., and Dobson, F., 1986, Introductory physics of the atmosphere and ocean: Dordrecht, D. Reidel, 126 p.

Hoffman, P.F., 1973, Evolution of an Early Proterozoic continental margin: The Coronation geosyncline and associated aulacogens of the northwestern Canadian Shield: Royal Society of London Philosophical Transactions, ser. A, v. 273, p. 547–581.

——1987, Proterozoic foredeeps, foredeep magmatism and Superior-type iron formations in the Canadian Shield, *in* Kröner, A., ed., Proterozoic lithospheric evolution: American Geophysical Union Geodynamics Series, v. 17, p. 85–98.

——1988, United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia: Annual Reviews of Earth and Planetary Sciences, v. 16, p. 543–603.

Hoffman, P.F., and Bowring, S.A., 1984, Short-lived 1.9 Ga continental margin and its destruction, Wopmay orogen, northwest Canada: Geology, v. 12, p. 68–72.

Hoffman, P.F., and Pelletier, K.S., 1982, Cloos nappe in Wopmay orogen: Significance for stratigraphy of the Akaitcho Group, and implications for opening and closing of an Early Proterozoic continental margin, *in* Current research, Part A: Geological Survey of Canada Paper 82-1A, p. 109–115.

Hoffman, P.F., Tirrul, R., and Grotzinger, J.P., 1983, The externides of Wopmay orogen, Point Lake and Kikerk Lake map areas, District of Mackenzie, *in* Current research, Part A: Geological Survey of Canada Paper 83-1A, p. 429–435.

Hoffman, P.F., Tirrul, R., Grotzinger, J.P., Lucas, S.B., and Eriksson, K.A., 1984, The externides of Wopmay orogen, Takijuq Lake and Kikerk Lake map areas, District of Mackenzie, *in* Current research, Part A: Geological Survey of Canada Paper 84-1A, p. 383–395.

Hoffman, P.F., Tirrul, R., King, J.E., St-Onge, M.R., and Lucas, S.B., 1988, Axial projections and modes of crustal thickening, eastern Wopmay orogen, northwest Canadian Shield, *in* Clark, S.P., Jr., ed., Processes in continental lithospheric deformation: Geological Society of America Special Paper 218, p. 1–29.

Irving, E., and McGlynn, J.C., 1979, Paleomagnetism in the Coronation geosyncline and arrangement of continents in the middle Proterozoic: Royal Astronomical Society Geophysical Journal, v. 58, p. 309–336.

Jakosky, B.M., 1986, Volcanoes, the stratosphere, and climate: Journal of Volcanology and Geothermal Research, v. 28, p. 247–255.

Lalonde, A.E., 1986, The intrusive rocks of the Hepburn metamorphic-plutonic zone of the central Wopmay orogen, N.W.T. [Ph.D. thesis]: Montreal, McGill University, 258 p.

Lucas, S.B., 1984, Low-grade metamorphism in the externides of Wopmay orogen, N.W.T. [B.S. thesis]: Kingston, Ontario, Queen's University, 163 p.

Miller, M.M., 1987, Dispersed remnants of a northeast Pacific fringing arc: Upper Paleozoic terranes of Permian McCleod faunal affinity, western U.S.: Tectonics, v. 6, p. 807–830.

Palmén, E., and Newton, C.W., 1969, Atmospheric circulation systems: New York, Academic Press, 603 p.

Pelechaty, S.M., and Grotzinger, J.P., 1988, Stromatolite bioherms of a 1.9 Ga foreland basin carbonate ramp, Beechey Formation, Kilohigok basin, Northwest Territories, *in* Geldsetzer, H., ed., Reefs from Canada and adjacent areas: Canadian Society of Petroleum Geologists Memoir 13 (in press).

Pollack, J.B., Toon, O.B., Sagan, C., Summers, A., Baldwin, B., and Van Camp, W., 1976, Volcanic explosions and climate change: A theoretical assessment: Journal of Geophysical Research, v. 81, p. 1071–1083.

Reichenbach, I.G., 1986a, An ensialic marginal basin in Wopmay orogen, northwestern Canadian Shield [M.S. thesis]: Ottawa, Ontario, Carleton University, 120 p.

——1986b, Geochemistry of ensialic marginal basin basalts, Wopmay orogen, northwestern Canadian Shield, *in* Proterozoic geochemistry abstracts: Lund, Sweden, International Geological Correlations Program, Project 217, p. 77–78.

Rose, W.I., and Chesner, C.A., 1987, Dispersal of ash in the great Toba eruption, 75 ka: Geology, v. 15, p. 913–917.

Scotese, C.R., 1984, An introduction to this volume: Paleozoic paleomagnetism and the assembly of Pangea, *in* Van der Voo, R., Scotese, C.R., and Bonhommet, N., eds., Plate reconstruction from Paleozoic paleomagnetism: American Geophysical Union Geodynamics Series, v. 12, p. 1–10.

Settle, M., 1978, Volcanic eruption clouds and the thermal power output of explosive eruptions: Journal of Volcanology and Geothermal Research, v. 3, p. 309–324.

Sigurdsson, H., and Carey, S.N., 1981, Marine tephrochronology and Quaternary explosive volcanism in the Lesser Antilles arc, *in* Self, S., and Sparks, R.S.J., eds., Tephra studies: Dordrecht, Netherlands, D. Reidel, p. 255–280.

Sigurdsson, H., Sparks, R.S.J., Carey, S.N., and Huang, T.C., 1980, Volcanogenic sedimentation in the Lesser Antilles arc: Journal of Geology, v. 88, p. 523–540.

Simkin, T., Siebert, L., McClelland, L., Bridge, D., Newall, C., and Latter, J.H., 1981, Volcanoes of the world: Stroudsburg, Pennsylvania, Hutchinson Ross, 232 p.

Sparks, R.S.J., 1986, The dimensions and dynamics of volcanic eruption columns: Bulletin of Volcanology, v. 48, p. 3–15.

St-Onge, M.R., and King, J.E., 1987a, Evolution of regional metamorphism during back-arc stretching and subsequent crustal shortening in the 1.9 Ga Wopmay orogen, Canada: Royal Society of London Philosophical Transactions, ser. A, v. 321, p. 199–218.

——1987b, Thermo-tectonic evolution of a metamorphic internal zone documented by axial projections and petrological *P-T* paths, Wopmay orogen, northwest Canada: Geology, v. 15, p. 155–158.

St-Onge, M.R., King, J.E., and Lalonde, A.E., 1982, Geology of the central Wopmay orogen (Early Proterozoic), Bear Province, District of Mackenzie: Redrock Lake and the eastern portion of the Calder River map areas, *in* Current research, Part A: Geological Survey of Canada Paper 82-1A, p. 99–108.

Tarney, J., Saunders, A.D., Mattey, D.P., Wood, D.A., and Marsh, N.G., 1981, Geochemical aspects of back-arc spreading in the Scotia Sea and western Pacific: Royal Society of London Philosophical Transactions, ser. A, v. 300, p. 263–285.

van Staal, C.R., 1987, Tectonic setting of the Tetagouche Group in northern New Brunswick: Implications for plate tectonic models of the northern Appalachians: Canadian Journal of Earth Sciences, v. 24, p. 1329–1351.

Walker, G.P.L., 1981, Generation and dispersal of fine ash and dust by volcanic eruptions: Journal of Volcanology and Geothermal Research, v. 11, p. 81–92.

Wilson, L., Sparks, R.S.J., Huang, T.C., and Watkins, N.D., 1978, The control of eruption column heights by eruption energetics and dynamics: Journal of Geophysical Research, v. 83, p. 1829–1836.

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