EVALUATING LATE NEOPROTEROZOIC GLACIO-AEOLIAN DEPOSITS FOR POTENTIAL TARGET PARAMETERS IN MODELING SNOWBALL EARTH WIND CONDITIONS

Ryan C. Ewing
University of Texas-Austin, Jackson School of Geosciences, Department of Geological Sciences, C1100, 1 University Station, Austin, TX 78712-0254

Abstract

Aeolian sandstones are found intimately associated with Late Neoproterozoic 'snowball Earth' glacial deposits. Studying the nature of these aeolian deposits offers the great potential to elicit new and important information regarding the wind conditions during these extreme glacial intervals. Wind direction is the dominant paleoclimatic indicator that can be derived from aeolian deposits and one that has been largely ignored in geologic and climatic modeling studies of a snowball Earth. This objective of this proposal is to initiate a study of Late Neoproterozoic glacio-aeolian deposits from a broad paleogeographic region to build an empirical model for global wind patterns surrounding the snowball Earth glaciations. These wind direction data will then be used as targets for global circulation model (GCM) simulations of a snowball Earth.

Introduction

The most abrupt and severe climatic excursion in the Earth's history may have occurred during the Late Neoproterozoic glacial intervals (Hoffman et al., 1998). Late Neoproterozoic glaciogenic deposits are found over most continents and paleomagnetic data indicate that these deposits originated in tropical regions (Evans, 2000; Hoffman and

Schrag, 2002; Kirschvink, 1992). These two pieces of evidence lead to the suggestion that the Earth was encased in ice during the Late Precambrian, termed the "snowball Earth" (Hoffman et al., 1998; Kirschvink, 1992). The hypothesis postulates that the reduced solar luminosity at that time combined with a low-latitude continental configuration stimulated a reduction in the atmospheric CO2, thereby reducing greenhouse effects and initiated a runaway ice/albedo feedback that lead the polar ice caps to extend to the equator within thousands of years (Hoffman et al., 1998; Kirschvink, 1992). The extension of glaciers at the tropics accounts for the observed glaciogenic diamictites. During the global glaciation the ocean and atmosphere would not interact and an atmospheric build up of greenhouse gasses would occur. The build up of greenhouse gasses could then reach a critical threshold that would initiate a runaway greenhouse, melting the ice and causing an abrupt and dramatic sea level rise on the time scale of ~2000 years (Allen and Hoffman, 2005; Hoffman et al., 1998; Kirschvink, 1992). In the aftermath of the snowball Hoffman et al. (1998) suggests that the high atmospheric CO2 resulted in the deposition of 'cap' carbonate rocks directly above the diamictites.

Only two studies have explicitly focused on deriving paleowind directions from Late Neoproterozoic glacio-aeolian sand bodies (Williams, 1998; Denyoux et al., 1989). This is likely due to the scarcity of such deposits and that most have focused on understanding the broader paleoclimate of the time. Observations from the two most well studied cases (Williams, 1998; Denyoux et al., 1989) show large-scale aeolian cross-bedded sandstones occurring along with glacial diamictites and other periglacial features (Figure 1). However, descriptions of many other non-aeolian Late Neoproterozoic glacial deposits (Halverson et al., 2002; Hoffman et al., 1998; Hoffman and Schrag, 2002; recognize aeolian deposits in the sequence (Figure 2). These deposits have not been adequately described in the published literature, nor has their role in the overall depositional models of the snowball Earth scenario been established. Further examination of these deposits for paleowind indicators along with a reevaluation of the well studied aeolian deposits may provide new information about the wind conditions surrounding the snowball Earth.

Allen and Hoffman (2005) use giant wave ripples for wave and wind hindcasting to predict extreme wind conditions in the aftermath of the snowball Earth. In their study they use the wavelengths of giant wave ripples to predict the period of sea surface gravity waves that yield estimates of sustained 20 m/s winds across a fetch unlimited basin (Figure 3). This type of evidence could augment Late Neoproterozic aeolian studies and both could provide useful targets for global climate models aimed at simulating snowball Earth conditions.

Much effort in the global climate modeling community has been directed toward verifying or disproving the snowball Earth hypothesis (Baum and Crowley, 2001; Hyde et al., 2000; Jenkins and Smith, 1999; Poulsen et al., 2001, 2002; Poulsen and Jacob., 2004; Pierrehumbert, 2004, 2005). The predominant focus of these models has been sensitivity testing of variable levels of atmospheric CO2 and different continental configurations (Chandler and Sohl, 2000; Poulsen et al., 2002). The results of these models have varied considerably due to inadequate modeling of the climate system details (Poulsen and Jacob, 2004). Specifically, wind driven ocean circulation has been suggested to be an underrepresented but critical factor in determining if a snowball Earth could have occurred (Poulsen et al., 2001; Poulsen and Jacob., 2004). An empirically derived model based on geological evidence from aeolian deposits would provide an observational target for climate models and reduce the uncertainty of the some climate system details.

A Late Neoproterozoic Glacio-Aeolian Depositional Model

Wide spread aeolian activity is associated with glacial intervals and should have figured prominently in the sedimentary record during the Late Neoproterozoic glaciations. Aeolian deposits occur at broadly similar stratigraphic levels in several studied snowball intervals. The aeolian deposits occur directly beneath or in place of the diamictites (Hoffman and Schrag, 2002; Williams, 1998) (Figure 2). A seemingly plausible scenario that may account for these observations lies in understanding the aeolian sediment state (Kocurek and Lancaster, 1999) of the snowball events in terms of sediment supply, sediment availability, and wind transport capacity. Enhanced tropical weathering on the low-latitude continents (Kirschvink, 1992) would generate a high sediment supply prior to the initiation of a snowball Earth. Without plant life to enhance chemical weathering in the soils the sand sized fraction of the sediment could be significantly. At this time a quiescent tropical climate would act to stabilize the sediment through high soil moisture or perhaps algal binding. However, as the climate grew colder consequently drier through the reduction of greenhouse forcing the newly generated sediment would become available for transport. A reduced hydrologic cycle would slow runoff potentially shutting down rivers and exposing sediment. Further, because of the growth of ice caps and glaciers, mean sea level would drop exposing continental shelves and a significant supply of sediment.

Allen and Hoffman (2005) point out that, high horizontal atmospheric pressure gradients during the deglaciation of a snowball event could drive high velocity winds. Similarly, as glaciers approached the equator prior to a snowball, a reduced hydrologic cycle reduces latent heat fluxes, increasing latitudinal temperature gradients (Pierrehumbert, 2002). The thermal contrasts would generate an extreme continentality effect causing high horizontal pressure gradients resulting in high winds that would mobilize the available sediment. The high availability of the sediment and high velocity wind conditions would be favorable to the accumulation of sediment creating the observed aeolian deposits. Pierrehumbert (2005) points out that during a snowball the low thermal inertia of the surface would result in a largely stabilized atmosphere and effects of wind would be reduced shutting down sediment transport.

During deglaciation the sediment would once again become available for transport and the high velocity should remobilize the sediment, however in many of the studied areas overlying aeolian deposits are not observed (Hoffman and Schrag, 2002) (Figure 2). This can be reconciled in several ways. The predicted rapid sea-level rise driven by the extreme post-glacial greenhouse would subaqueously remobilize the sediment, removing it from its depositional origin and remove the aeolian signature. Also, many of the studied areas focus on low-latitude carbonate platforms and ramps devoid of siliciclasitic sediments. Further evidence of aeolian activity pre and post snowball may be found by investigation of mid and higher latitude continental and marginal marine deposits.

Of the aeolian sand bodies preserved in the rock record at this time most are continental and marginal marine (Denyoux et al., 1989; Williams, 1998).

GCM Predicted Circulation Patterns for a Snowball Earth

Surface wind patterns surrounding the snowball Earth are not explicitly addressed in most GCM studies of the Late Neoproterozoic climate. However, general circulation patterns that may influence the aeolian transport and deposition of sediments can be determined from some studies. The large low-latitude continental land mass and the advance of the glaciers to the mid and low latitudes is the predominant factor controlling the wind patterns during snowball conditions (Baum and Crowley, 2001; Donnadieu et al., 2004; Jenkins and Smith, 1999; Lewis et al., 2003; Poulsen and Jacob, 2004). The configuration of the continents used in the GCMs can have a considerable impact on the circulation patterns. Poulsen and Jacob (2004) use an idealized low to mid-latitude super continent and simulate strong cross-equatorial winds, driven by strong seasonal thermal contrasts and resulting latitudinal pressure differences (Figure 4). This has a significant impact on the wind-driven ocean circulation. The result is enhanced ocean heat transport that does not allow a snowball condition to occur. Figure 4 shows that the expected equatorial trade winds in their model are suppressed. Baum and Crowley (2001) use a realistic continental configuration and simulate a standard trade wind pattern and enhanced westerlies in the northern hemisphere (100% stronger than their control run) (Figure 5). The southern hemisphere westerlies in their model shift 15 degrees to the south and are suppressed compared to their control run (Figure 6). Baum and Crowley

(2001) attribute this shift to the large south polar ice sheet causing enhanced anticyclonic winds blowing opposite to the westerlies. The predicted wind patterns of Baum and Crowley (2001) are consistent with other studies that show enhanced mid-latitude winds and an equatorial shift in the Jet Stream (Donnadieu et al., 2004; Jenkins and Smith, 1999).

Proposed Work

The proposed research will target two areas, the collect of geological evidence from aeolian deposits for paleowind indicators to be used as target parameters in a GCM and the implementation of a realistic GCM to do sensitivity testing to achieve the target parameters. The predominant factor limiting the collection of paleowind data is that the deposits must have a well supported paleogeographic location based on strong paleomagnetic evidence and the deposits must encompass the Late Neoproterozic glacial intervals based on strong radiometric dating evidence. Another limiting factor in collecting paleowind data from aeolian deposits is the influence of local topography on dune orientation. Several proposed mountain belts occur during the Neoproterozoic (Dalziel, 1997), but detailed paleotopography is unknown.

Because the goal of collecting paleowind data is to develop an empirical model for global paleowind patterns data will be collected from a broad geographic distribution. A broad latitudinal distribution would be useful for reconciling discrepancies in current GCMs (Poulsen and Jacob, 2004; Baum and Crowley, 2001). Figure 7 shows the localities of known Late Neoproterozoic glacio-genic deposits in both their modern and

Neoproterozoic (600 Ma) configurations. Previously collected data from these locations can be used if available. Alternatively field work will be employed to collect the data.

The goal of using paleowind data in a GCM is to more realistically model snowball Earth conditions and perhaps narrow the parameterization of factors influencing circulation patterns at that time. Paleogeography is an important boundary condition in snowball GCMs. Because the data will be collected from specific paleogeographic locations a realistic continental configuration will be used in the model. The role of ocean processes has been suggested as a major factor controlling snowball Earth conditions (Poulsen, 2001; Poulsen and Jacob, 2004). Various parameterizations of the ocean currents, transient eddies and vertical mixing will be used vary oceanic heat transport to adjust the model for the target wind conditions. The presence of significant ice on the continents may also influence latitudinal thermal contrast through enhanced albedo that could control circulation patterns. This will also be used as a sensitivity test to achieve the target parameters.

Summary

Aeolian deposits associated with the Late Neoproterozoic glaciations are understudied and offer the potential to be used as targets for GCM models of the snowball Earth. A thorough investigation of aeolian deposits from wide-ranging paleogeographic localities will be studied and paleowind data from these localities will be collected. These data will then be employed in GCM models and sensitivity testing using varied ocean processes and surface albedo effects to achieve the target parameters.

References

Baum, S.K. and Crowley, T.J. 2001. GCM response to late Precambrian (~590Ma) ice-covered continents. Geophysical Research Letters. v. 28, n. 4, p. 583-586.

Baum, S.K. and Crowley, T.J. 2003. The snow/ice instability as a mechanism for rapid climate change: A Neoproterozoic snowball Earth model example. Geophysical Research Letters. v. 30, n. 20, 2030.

Chandler, M.A. and Sohl, L.E. 2000. Climate forcings and the initiation of low-latitude ice sheets during the Neoproterozoic Varanger glacial interval. J. Geophysical Research, v. 105, n. D16, p. 20,737-20,756.

Dalziel, I.W.D. 1997. Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculation. GSA Bulletin, v. 109, n. 1, p. 16-42.

Deynoux, M., Kocurek, G., Proust, J. Late Proterozoic periglacial aeolian deposits on the West African Platform, Taoudeni Basin, western Male. Sedimentology, v. 36, p. 531-549.

Donnadieu, Y., Ramstein, G., Fluteau, F., Roche, D., Ganopolski, A. 2004. The impact of atmospheric and oceanic heat transports on the sea-ice-albedo instability during the Neoproterozoic. Climate Dynamics, v. 22, p. 293-306.

Hyde, W.T., Crowley, T.J., Baum, S.K., Peltier, R. 2000. Neoproterozoic ‘snowball Earth’ simulations with a coupled climated/ice-sheet model.

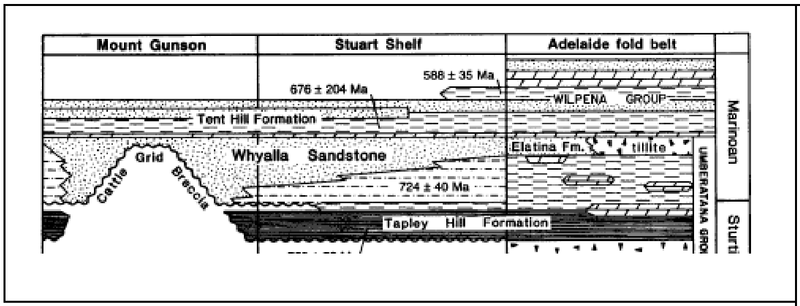
Jenkins, G.S. 2003. GCM greenhouse and high-obliquity solutions for early Proterozoic glaciation and middle Proterozoic warmth. J. of Geophysical Research, v. 108, n. D3, p. 4118.

Jenkins, G.S. and Smith, S.R. 1999. GCM simulations of snowball Earth conditions during the late Proterozoic. Geophysical Research Letters, v. 26, n. 15, p. 2263-2266.

Kirschivink, J. 1992. Late Proterozoic low-latitude global glaciation: the snow-ball earth. In: The Proterozoic Biosphere (J.W. Schopf and c. Klein, eds), p.51-52. Cambridge University Press, Cambridge.

Poulsen, C.J., Jacob, R.L., Pierrehumbert, R.T., Huynh, T.T. 2002. Testing paleogeographic controls on a Neoproterozoic snowball Earth. Geophysical Research Letters, v. 29, n. 11, 10-1.

Poulsen, C.J., Pierrehumbert, R.T., Jacob, R.L. 2001. Impact of ocean dynamics on the simulation of the Neoproterozoic "snowball Earth". Geophysical Research Letters, v. 28, n. 8, p. 1575-1578.



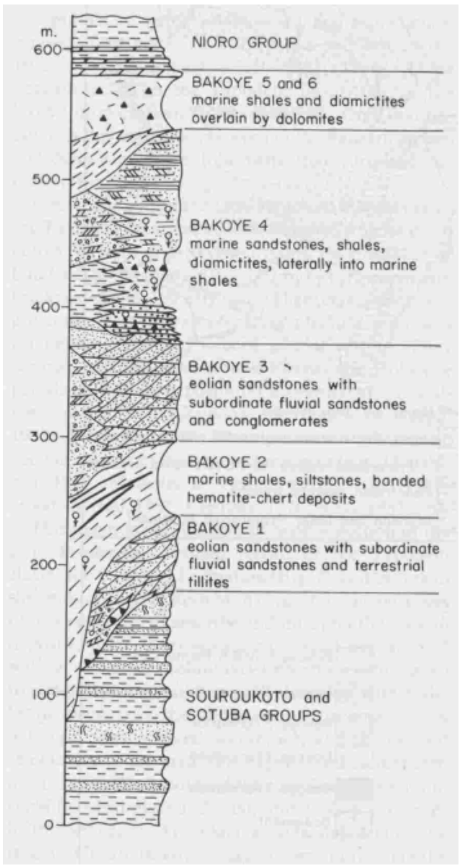


Figure 1. Two examples of aeolian sandstones occurring with glacial diamictites (Denyoux et al., 1989; Williams, 1998).

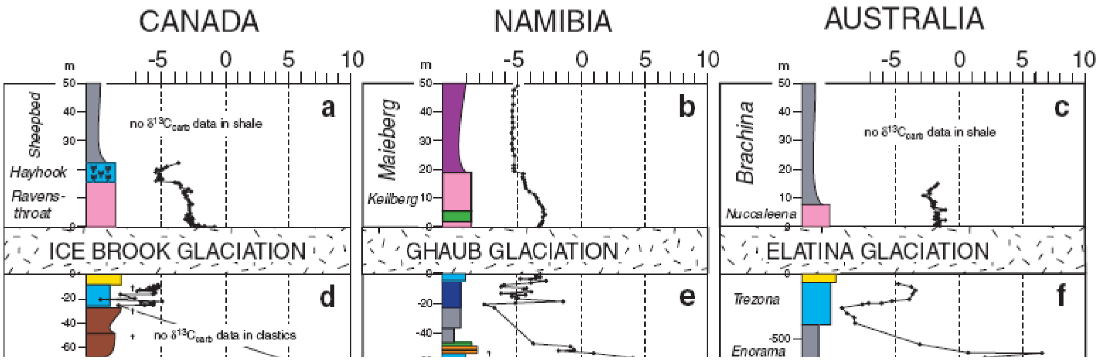


Figure 2. Examples of aeolian sandstones directly beneath interpreted snowball glaciations (Hoffman and Schrag, 2002).

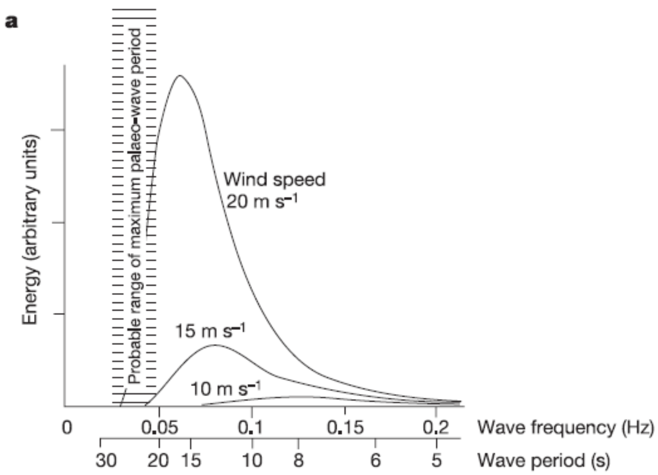


Figure 3. Allen and Hoffman (2005) estimate up to 20 m/s wind velocities during deglaciation of the snowball Earth.

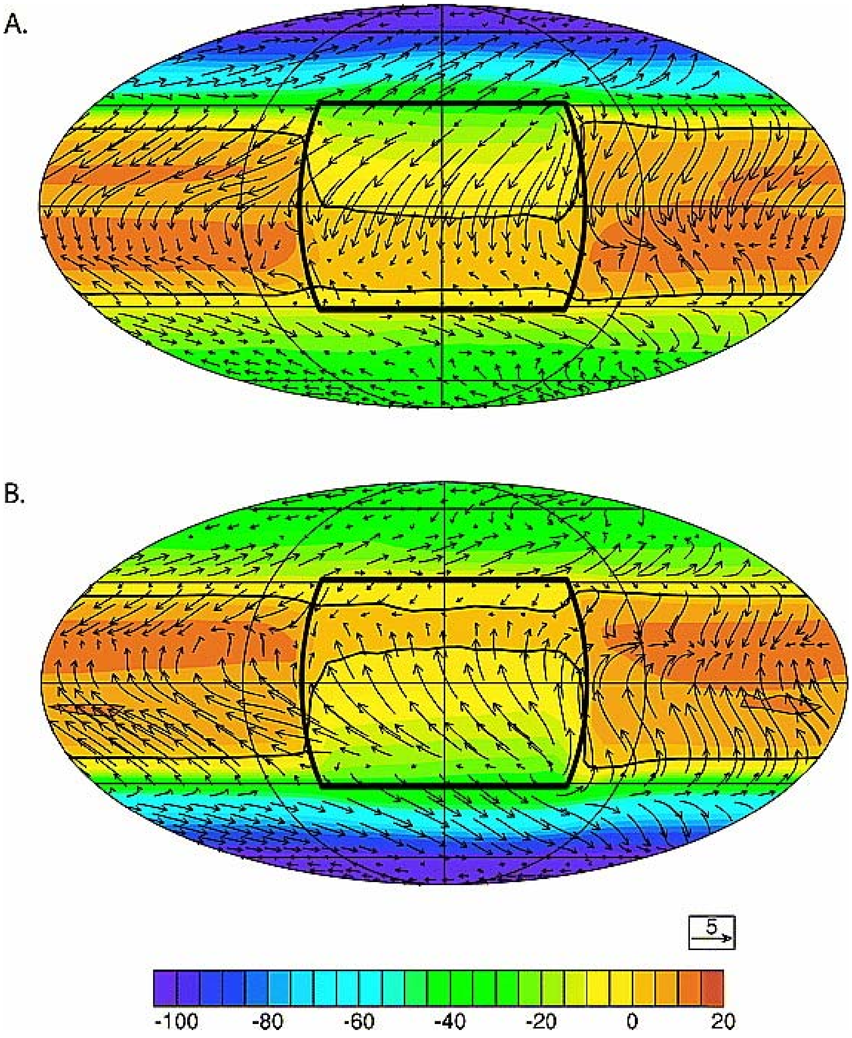


Figure 4. Surface wind map showing the influence of seasonal wind changes on sea surface temperatures. The thick line is the outline of an idealized supercontinent used in the model.
A. Northern hemisphere winter
B. Southern hemisphere winter
Note the cross-equatorial wind breaking the trade wind patterns. (Poulsen and Jacob, 2004).

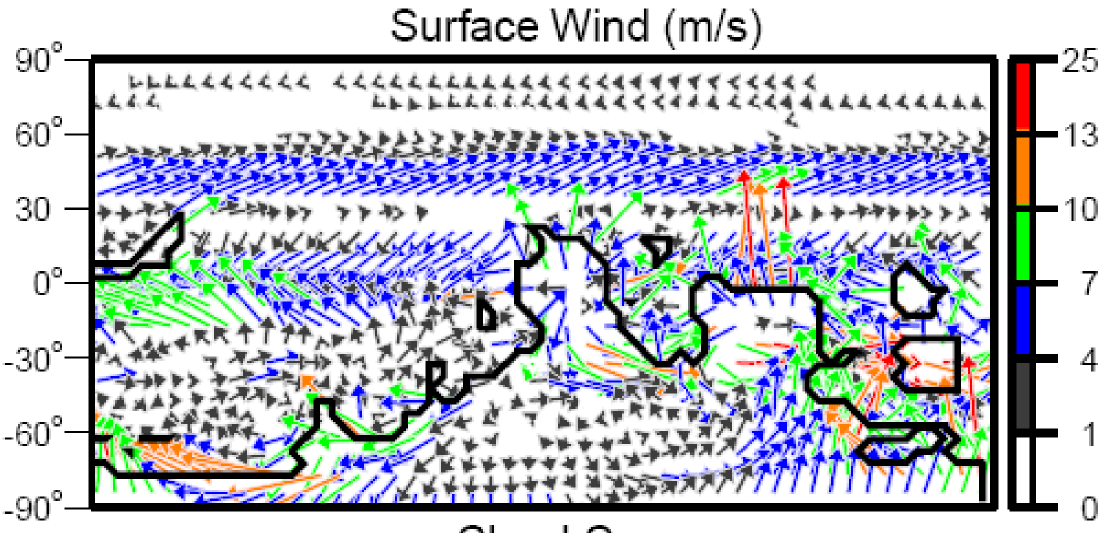


Figure 5. Surface wind map by Crowley and Baum (2001) indicates intensified northern hemisphere westerlies and suppressed southern hemisphere westerlies. The continental configuration here allows for more normal trade wind patterns compared with Poulsen and Jacob (2004).

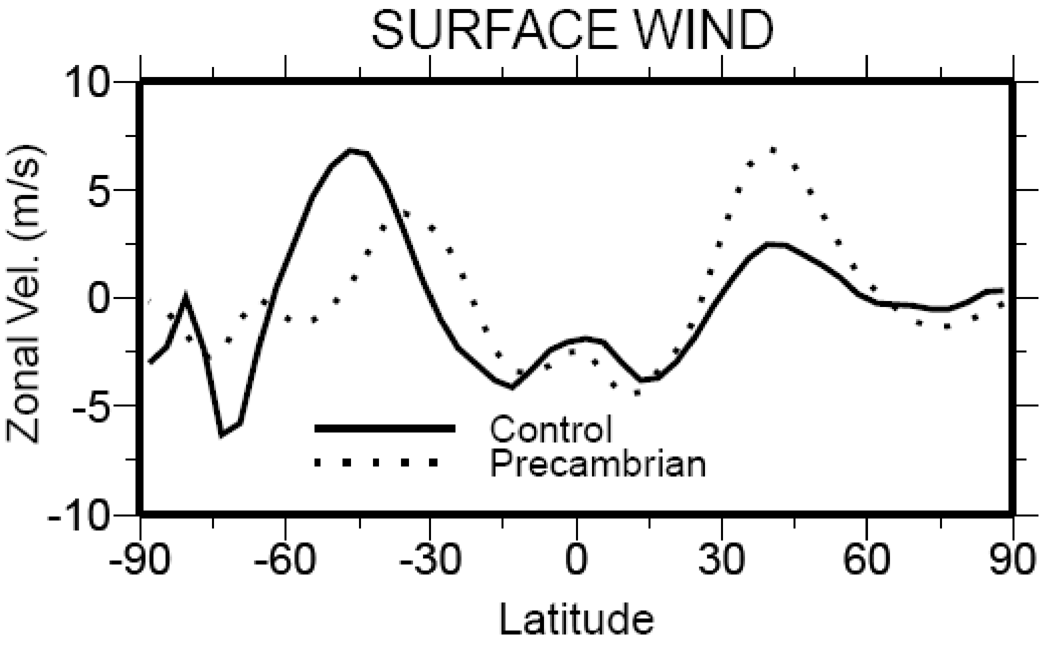


Figure 6. Zonal wind velocities from Crowley and Baum (2001). Note the enhanced mid-latitude winds.

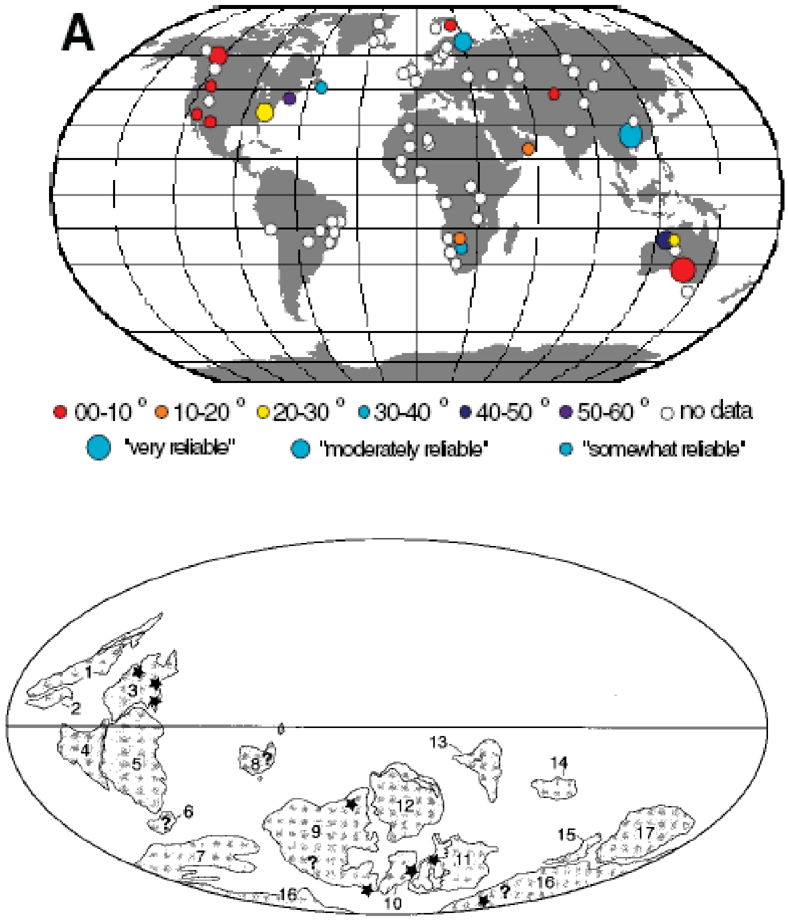


Figure 7. Upper figure shows the localities of Late Proterozoic glacio-genic deposits , their paleolatitude and reliability based on paleomagnetic evidence (Schrag et al., 2002). The Lower figure shows their distribution on the paleocontiental configuration (Chandler and Sohl, 2000).