Precambrian and Phanerozoic postglacial processes

Grant M. Young*
Department of Earth Sciences, University of Western Ontario, London, Ontario N6A 5B7, Canada

From their investigation of the Late Ordovician Soom Shale, Gabbott et al. (2010, p. 1103 in this issue of *Geology*) have produced an extremely detailed account of important relationships between sedimentological and organic processes during the dying phases of the short-lived Hirnantian glaciation in South Africa. They suggest that eolian input played a key role in stimulating growth of phytoplankton, so that bottom sediments were characterized by unusual aggregates of silt-size grains intimately associated with organic material. These organic-rich silty layers and lenses occur together with inorganic mudstone laminae deposited from nepheloid plumes and weak turbidity currents thought to be associated with fluvial input. In seeking an explanation for the remarkable preservation of fossilized metazoan organisms in the Soom Shale Lagerstätte, they suggest that organic productivity, stimulated by introduction of eolian material, may have played a pivotal role in the development of eutrophication and anoxic bottom conditions. This interesting account draws on disparate lines of evidence to bring into focus a rare picture illustrating interactions between sedimentological and organic processes during a very special period accompanying the rapid demise of an ice sheet. Gabbott et al.'s detailed investigation begs the question of what evidence we have regarding conditions following older, possibly much more prolonged and extensive, glaciations, when the composition of Earth's atmosphere was probably different and organic evolution was at a much more primitive stage—for example, when there were no land plants or metazoans. In this different world, was deglaciation accompanied by the development of anoxic conditions? Was there significant eolian input because of the dearth of terrestrial plants? How may the Snowball Earth hypothesis (SEH) contribute to our understanding of ancient postglacial events? How do Neoproterozoic banded iron formations and postglacial "cap carbonates" fit into the picture, and how do we accommodate the accumulating evidence from stable isotopes? There are many questions, but few satisfactory answers. The following is an attempt to briefly consider some aspects of postglacial phenomena throughout geological time.

Most studies of Quaternary and recent glacial deposits are, for practical reasons, carried out in terrestrial settings (Martini, 1997), but the majority of ancient glacial sedimentary rocks are marine. Inasmuch as they can be accurately read from the fragmentary sedimentary rock record, climatic conditions on Earth appear to have fluctuated dramatically throughout its long history. In fact, it could be argued that most organic evolution (including the emergence of our own species) occurred in response to climatically induced environmental pressures. Among the most easily recognized paleoclimatic signals are those of ancient glaciations. The criteria are simple and few: the presence of striated rock or sediment surfaces beneath suspected glacial deposits; the occurrence of widespread diamictites—conglomerates with clasts scattered through an abundant matrix; dropstones, which are large, isolated rock fragments in finely bedded sedimentary rocks; and ancient varved deposits that record annual freeze-and-thaw cycles in ancient lakes. There are many caveats and more sophisticated criteria, but the field observations are critical.

Existing data suggest that, during its ~4.6 g.y. history, significant portions of Earth's surface were sporadically covered by glaciers. There are hints of Archean glaciations, mostly from South Africa where diamictites and dropstones occur in rocks of the Pongola Supergroup (ca. 2.9 Ga), and possible equivalents in the Government Subgroup of the Witwatersrand Basin (Von Brunn and Gold, 1993). There is, however, little published information on deglaciation products following decay of these oldest known glaciers.

The next glacial deposits are in the Huronian Supergroup (ca 2.47–2.2 Ga), on the north shore of Lake Huron in Ontario, Canada. Glacial deposits are present at three separate stratigraphic levels in the thick (up to 12 km) Huronian Supergroup: the Ramsay Lake, Bruce, and Gowganda Formations. Among these, the thickest, most widespread and best known is the Gowganda Formation. The internal stratigraphy of the Gowganda is extremely complex and variable (Lindsey, 1969; Miall, 1985; Young and Nesbitt, 1985). The upper part of the Gowganda Formation, which shows no physical evidence of glacial activity, consists of one or several coarsening-upward cycles from fine laminated mudstones to sandstones, which have been interpreted as prograding deltaic deposits (Lindsey, 1969; Rainbird and Donaldson, 1988; Junnila and Young, 1995). The terrestrial landscape of Palaeoproterozoic times would likely have been largely devoid of vegetation and susceptible to deflation, but significant eolian input has not been reported from these ancient postglacial deposits. It has been suggested that the Huronian glaciations were widespread in North America and possibly elsewhere (Ojakangas, 1988; Young, 2004), and it has even been proposed that the entire surface of Earth was frozen at that time (Kirschvink, 1992).

Such global "icehouse" conditions were first envisaged by Mawson (1949) and Harland (1964) for widespread Neoproterozoic (ca. 1000–540 Ma) glacial deposits. The catchy phrase "Snowball Earth" was coined by Kirschvink (1992), but the Snowball Earth hypothesis received a strong boost following publication of a paper by Hoffman et al. (1998), and the subsequent firestorm of discussions and counter-arguments. The snowball condition is explained by runaway albedo—glaciers build up in continental areas at high latitudes and altitudes, then cooling is exacerbated as the expanding snow and ice cover reflects solar energy back into space (Bodyko, 1969). This suggestion was largely ignored because of the lack of a mechanism to rescue the planet from a permanently frozen condition. The geological record clearly shows that the cycle *was* broken and the ice receded. But what brought about deglaciation, and what was the nature of postglacial sediments?

It was suggested by Hoffman et al. (1998, and in subsequent publications), that the Late Neoproterozoic (Cryogenian) glaciations ended abruptly because of the greenhouse effect—critical buildup of CO_2 in the atmosphere, due to ongoing plate tectonic activity while the Earth was ice-bound. Catastrophic demise of glaciers and icecaps was envisaged, accompanied by a rapid rise of surface temperatures and sea level, and extreme weathering due to the low pH (high atmospheric CO_2) of rainwater and elevated temperatures. The common occurrence of "cap carbonates" above glacial diamictites was cited as evidence of these extreme conditions, as was their stable isotopic signature. Thus, postglacial sedimentation in Cryogenian times was commonly characterized, not by laminated shales showing evidence of anoxic conditions, but by so-called cap carbonates. Many cap carbonates occur above diamictites with a high carbonate clast content. An independent way of testing these ideas is to look at the major element composition of postglacial fine-grained siliciclastic

*E-mail: gyoung@uwo.ca.

deposits, using the Chemical Index of Alteration, (CIA) (Nesbitt and Young, 1982). Many Neoproterozoic glaciogenic successions contain a high percentage of carbonate clasts (both limestones and dolostones), so interpretation of the CIA values of postglacial mudstones is difficult because Ca is one of the elements used in the calculation. Postglacial Paleoproterozoic mudstones of the upper Gowganda Formation, which are not "contaminated" with carbonate, show an upward increase in CIA values (Young and Nesbitt, 1999, their figure 6), such as might be predicted at the end of a "normal" Pleistocene-type glaciation, as climate ameliorated and weathering processes accelerated. The SEH predicts that post-glacial siliciclastic sediments should show the opposite trend, with initial extreme weathering (due to high CO_2 content in the atmosphere) and gradual upward decrease (lower CIA values) as surface-weathering reactions proceed and CO_2 drawdown takes place. Thus, major element geochemistry of postglacial mudstones may provide an important window into the nature of ancient ice ages.

Advocates of the SEH have also pointed to occurrences of banded iron formations in postglacial successions of Cryogenian age (Kirschvink 1992) as supporting evidence for their hypothesis. Such iron-rich sedimentary rocks are widespread in Paleoproterozoic successions, where they are commonly attributed to oxygenation of the atmosphere and hydrosphere. Their reappearance in younger successions was not anticipated, for it was argued that, because of terminal oxygenation of the atmosphere and oceans, they could no longer form. Putative return of reducing conditions to the world's oceans was attributed to isolation of oceans and atmosphere by a thick ice cover during severe glaciation. This, together with input of dissolved iron, mainly from hydrothermal circulation at oceanic spreading centers, was considered to cause build-up of iron in the oceans. With re-introduction of oxygen to the oceans as the ice cover receded, it was argued that iron formations would form. Thus banded iron formations have been regarded as a product of postglacial deposition in the Cryogenian, comparable in its timing to the Soom Shale, but produced by global oxidation of the oceans. In some cases, however, such as the Rapitan succession in the northern part of the North American Cordillera, banded iron formations occur *beneath* thick glaciogenic diamictites, and are not therefore a true postglacial phenomenon (Yeo, 1981). In addition, such iron formations are only associated with a few of the many Cryogenian glacial deposits. An alternative hypothesis (Yeo, 1981) is that these young banded iron formations resulted from hydrothermal activity in small, locally developed Red Sea–type basins where glaciers descended to sea level. Precipitation of Fe was brought about by mixing and dilution of Fe-rich hydrothermal water.

The understanding of ancient sedimentary rocks depends largely on the Huttonian Principle of Uniformitarianism. Most criteria for the recognition and interpretation of ancient glacial and postglacial deposits have been gleaned from our own serendipitous appearance on Earth during one of the rare glacial periods. The story of deglaciation involves melting icecaps, rising sea levels, and transgression and deposition of fine-grained silicilastic sediments (Gabbott et al., 2010), but even today, we can see many variations on that simple theme. In many formerly glaciated areas, isostatic rebound has outstripped postglacial eustatic sea-level rise (e.g., Finland), resulting in regression. Climatic change has also been significantly affected by plate tectonic phenomena. Earth's oceans and atmosphere, crust and interior have changed through time. We see the past through a glass darkly but wise interpretation of ancient sedimentary deposits demands understanding of these changes. Like the study by Gabbot et al., future investigations should embrace diverse techniques, but they must start and finish with meticulous attention to field work which, sadly, is becoming a lost art.

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Printed in USA