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Invited review

Sedimentology of the Neoproterozoic (c. 580 Ma) Squantum 'Tillite', Boston Basin, USA: Mass flow deposition in a deep-water arc basin lacking direct glacial influence

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ABSTRACT

The Squantum 'Tillite' (c. 593–570 Ma) consists of thick (up to 215 m) massive and crudely-stratified diamictites conformably interbedded with subaqueously-deposited conglomerates and sandstones within a thick (~7 km) Boston Basin fill which is dominated by argillite turbidites. The Squantum Tillite was first interpreted as being glacigenic in origin in 1914 because of the presence of diamictites; argillites were interpreted as glaciolacustrine 'varves' with rare ice-rafted debris, and conglomerates as glaciofluvial outwash. More recently these have been shown to be the product of deep marine mass flow processes with no glacial influence, yet because of its age equivalence with the deep marine, glacially-influenced Gaskiers Formation, the Squantum Tillite is still seen by some as supporting evidence for a widespread 'Snowball Earth' event at c. 580 Ma. New sedimentological work confirms that conglomerate and sandstone facies are deep marine sediment gravity flows genetically related to massive (homogeneous) and crudely-stratified (heterogeneous) diamictites produced subaqueously by downslope mixing of gravel and cobbles with muddy facies. Rare horizons of 'ice rafted debris' in thin-bedded and laminated turbidite facies interbedded with thick debrites show a weak but positive correlation of lamina thickness with grain size, suggesting these facies are non-glacial co-genetic 'debrite–turbidite' couplets. A significant volcanic influence on sedimentation is identified from reworked lapilli tuff beds and reworked ash in turbidites. The depositional setting of the Squantum 'Tillite' appears to be that of a submarine slope/fan setting in an open marine volcanic arc basin receiving large volumes of poorly-sorted sediment on the mid-latitude active margin of Gondwana. No direct glacial influence is apparent.

1. Introduction

The Neoproterozoic Era (c. 800–550 Ma) saw major changes in the Earth's geography involving the breakup of Rodinia and the assembly of Gondwana (Dalziel, 1997; Torsvik, 2003), repeated glacial events (Fairchild and Kennedy, 2007) and the appearance of complex, multicellular animals (Narbonne, 1998; Butterfield, 2007). A key uncertainty is the nature and variability of Neoproterozoic glacial climates. As many as four episodes of catastrophically cold glacial events followed by very hot interglacial conditions, marked by large magnitude (several hundred meters) glacioeustatic sea level fluctuations, are proposed ('Snowball Earth' Hoffman et al., 1998; Hoffman and Schrag, 2000, 2002; Kirschvink, 2002; MacDonald et al., 2010). The Snowball Earth hypothesis has triggered intense debate; much of the glacial sedimentary record can be interpreted in contrast, using well-known 'temperate' Phanerozoic glacial depositional models with abundant meltwater and open marine conditions (Eyles and Januszczak, 2004; Olcott et al., 2005; Eyles, 2008; van Loon, 2008). In fact, the archetypical Neoproterozoic 'glacial' succession consists of subaqueously deposited diamictites conformably interbedded within thick (km-scale) deep marine turbidites (Schermerhorn, 1974; Eyles and Januszczak, 2004; Eyles, 2008; van Loon, 2008) recording reworking of glacial deposits downslope into deep marine environments in tectonically active settings (commonly rifts); terrestrial facies are rarely preserved (e.g. in Northwest Africa; Proust and Deynoux, 1994). Many of these deep marine diamictites lack any glacial imprint and are marine debrite–turbidite successions deposited in rift basins lacking any ice cover (Eyles, 1993). Available age dating for diamictites found within known glaciated basins also suggests that diamictite deposition was diachroneous and likely to be the product of an evolving tectono-topographic control on the timing of glaciation (Eyles and Januszczak, 2004; Eyles, 2008).

This paper describes the sedimentology and stratigraphy of the Squantum Tillite (classically known as the Squantum Member), a classic Neoproterozoic diamictite deposit within the volcanic–sedimentary strata of the Boston Bay Group of the Neoproterozoic Boston Basin in eastern Massachusetts, USA. This diamictite deposit has a long history of study which demonstrated a deep marine origin by mass flow processes (see Dott, 1961), but is still regarded as glacial and evidence of a 'Snowball

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Earth Event' (the Gaskiers glaciation c. 580 Ma; Narbonne and Gehling, 2003; Halverson et al., 2005; Kawai et al., 2008; Hoffman and Li, 2009; Evans and Raub, 2012). Alternatively, others favor a glaciomarine setting with abundant meltwater (Socci and Smith, 1987; 1990; Passchier and Erukanure, 2010) or an entirely non-glacial marine setting free of any glacial influence (Crowell, 1957; Dott, 1961; Schermerhorn, 1974; Bailey, 1987; Thompson, 1993). The overall aim of this study was to evaluate these different models by sedimentological field work at key outcrops and to determine the broader significance of the Squantum Member for reconstructions of Neoproterozoic paleoclimates.

2. Physical setting and stratigraphy

The Boston Basin is a back-arc basin within the Avalon Terrane of eastern Newfoundland, Canada and southeastern New England, USA (Thompson and Bowring, 2000; Murphy et al., 2004). During the Neoproterozoic (c. 650 Ma), the Avalon Terrane formed part of the Avalonian–Cadomian Orogenic Belt along the northern subducting margin of Gondwana at moderate paleolatitudes of 30° S to 45° S until ca. 575 Ma, with some workers supporting a paleoposition near or adjacent to the West African craton (e.g. McNamara et al., 2001; Thompson et al., 2007) and others favoring a paleoposition closer to the Amazonian craton (Fig. 1) (e.g., Samson et al., 2005; Balintoni et al., 2010). Alternatively, paleomagnetic constraint estimates of Evans (2000) and Evans and Raub (2012) place the Avalon Terrane of Southeastern New England at 55° +8°/−7°. Now detached from Gondwana, these terranes are presently scattered around the margins of the North Atlantic Ocean along the eastern margin of North America (Southeastern New England), Atlantic Canada (Newfoundland, New Brunswick, and Nova Scotia), and Northwestern Europe (France, Bohemia, and southern Britain) (Murphy et al., 1999).

The Boston Basin extends from the northern suburbs of the City of Boston to the southern shore of Rhode Island and is bounded on its northern, western and southern margins by high-angle thrust faults; its eastern coastal boundary is poorly known (Billings, 1979; Skehan and Rast, 1983) (Fig. 2A, B). Underlying basement rocks are the Dedham and Westwood calc-alkaline granitoids (c. 625–600 Ma; Hepburn et al., 1993; Thompson and Bowring, 2000), the younger Mattapan–Lynn Volcanic Complex (c. 597–596 Ma; Durfee Cardoza, 1987) of rhyolitic, andesitic, and basaltic flows, dikes, breccias, scoria and lahars (Rast and Skehan, 1983; Thompson et al., 1996) with pillow lavas, and pyroclastics of the Brighton Volcanics (c. <587 Ma; Thompson and Grunow, 2004). These volcanic rocks record the oblique subduction of the Avalon Terrane beneath the northern Gondwanan margin and the development of magmatic arcs and arc basins between c. 640–570 Ma (Thompson, 1985; Murphy et al., 1999).

The stratigraphy of the Boston Bay Group has long been described in terms of a simple layer-cake model consisting of a lowermost succession consisting of the Roxbury Conglomerate (c. 597 Ma: Ault et al., 2004) composed of a 150–1300 m thick lowermost Brookline Member (dominantly conglomerate), a 180–500 m thick middle Dorchester Member (argillite turbidites with minor conglomerate) with the 18–215 m thick upper Squantum Member (Squantum 'Tillite' of Sayles, 1914) (Bailey et al., 1976) of diamictites, minor sandstones and siltstones, and an uppermost succession (Cambridge Argillite c. 570 Ma; Thompson and Bowring, 2000) consisting of 5.5 km of tuffaceous, finely-laminated to thin-bedded argillite turbidites. This model is based on the assumption that diamictites are 'tillites' that were deposited coevally as a horizontal horizon across the full extent of the basin (see Sayles and LaForge, 1910; Sayles, 1914). Many workers have noted that this is incorrect (Dott, 1961; Bailey et al., 1976; Socci and Smith, 1987). The basin fill stratigraphy is, in fact, highly complex because of syndepositional faulting and a structural control on local depocenters and the repetition of facies through time (Thompson, 1993). As we shall show below, some broad generalizations are possible based on paleocurrent directions and facies distributions but presentation of a detailed basin stratigraphy is not possible given a lack of adequate subsurface data control.

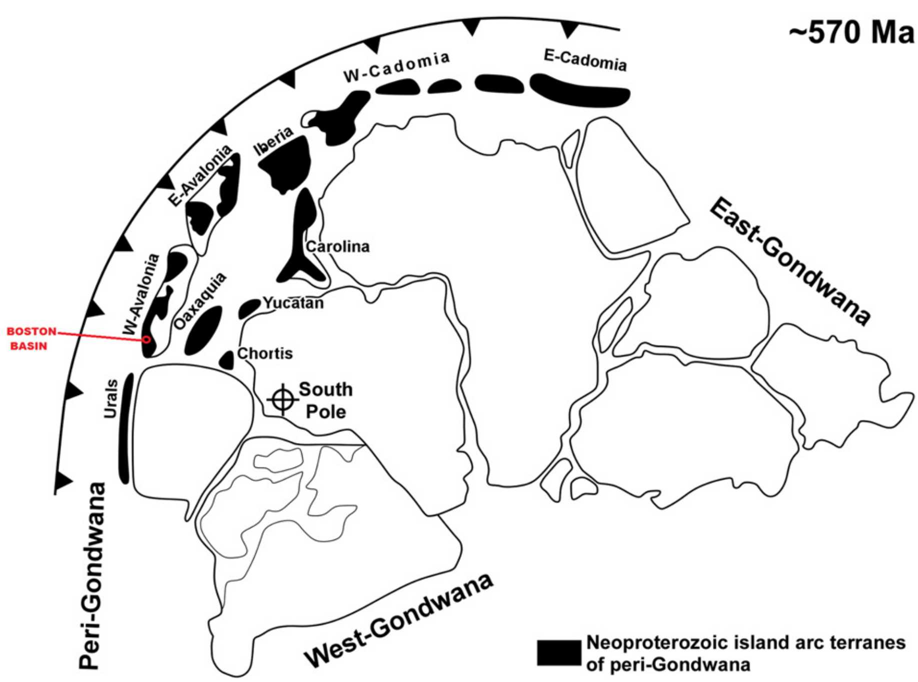

Fig. 1. Reconstruction of Gondwana at c. 570 Ma showing paleogeographic position of the Neoproterozoic island arc peri-Gondwana terranes (Avalonian–Cadomian Terranes). Paleogeographic location of the Boston Basin within Western Avalonia (W-Avalonia on figure) is shown on figure.
Reconstruction of Gondwana modified from Balintoni et al. (2010).