Sedimentary Geology 322 (2015) 19–33

Contents lists available at ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

The significance of ice-rafted debris in Sturtian glacial successions

D.P. Le Heron

Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey TW200BY, United Kingdom

ARTICLE INFO

Article history:
Received 6 January 2015
Received in revised form 1 April 2015
Accepted 2 April 2015
Available online 14 April 2015

Keywords:
Dropstone
Snowball Earth
Glacial
Neoproterozoic
Cryogenian
Sturtian

ABSTRACT

Globally, Sturtian (early Cryogenian) glacial deposits are well expressed, and belong to the oldest Neoproterozoic icehouse Earth event. The evidence for glaciation typically includes the phenomena such as striated pavements, striated clasts in diamictites, and abundant dropstones. More problematic, and potentially more significant, are intercalated deposits that exhibit no apparent evidence of a glacial influence on deposition. These apparently non-glacially-influenced intervals may represent deposition during interglacial periods, or at times when ice sheets transitioned to cold-based ice masses where sediment advection into basins was suppressed. Here, using three case studies from South Australia, northern Namibia, and Death Valley (USA), we show that many IRD-free intervals occur at the top of backstepping successions, where they are best interpreted as glacial minima deposits. In other cases, the volume of IRD in a succession shows less distinct increases and decreases upsection. Rhythmic intercalation of IRD-bearing and IRD-free intervals with glaciomarine turbidites can also be observed. These latter examples may be interpreted to record variations in debris content of ice margins, switch on/switch off of ice streams, or simply dynamic oscillation of a hinterland ice margin.

1. Introduction

The Sturtian interval (ca. 715 Ma; Macdonald et al., 2010a) represents the first of three intense glaciations that affected Earth during the Cryogenian. Sedimentological considerations point to highly dynamic, warm-based to polythermal ice masses at this time (Etienne et al., 2007; Allen and Etienne, 2008; Arnaud and Etienne, 2011), discrediting the idea of a "hard" snowball Earth, but not inconsistent with a "soft" snowball or slushball Earth (Fairchild and Kennedy, 2007). The Sturtian glaciation is estimated to span 55 Ma based on Re–Os dates from Canada (Rooney et al., 2014), and based on Pleistocene analogues it is reasonable to suppose that the intensity of glaciation varied throughout this period. Major questions include the location of palaeo-ice sheet grounding lines, how much of the sedimentary record was deposited beneath floating ice shelves, and the number of glacial cycles recorded in each outcrop belt that exposes Sturtian-age strata.

An excellent glacial archive in areas such as Australia, Namibia, and Death Valley (Arnaud et al., 2011, and refs therein) (Fig. 1) reveals intervals apparently lacking in ice rafted debris (IRD). The potential for multiple glacial cycles is clear, raising the question of whether they represent allocyclic patterns of regional or even global advance–retreat cycles, or if they are simply local phenomena. The main aim of this paper is thus to determine the palaeoclimatological significance of the IRD-free intervals. A three step approach is taken: (1) establishing palaeo-ice sheet presence or the case for glaciation using a variety of sedimentological indicators, (2) considering the mechanisms for IRD emplacement in a succession, and (3) evaluating the stratigraphic context of IRD within a sequence stratigraphic interpretive framework. The latter step involves the description and interpretation of data from three case study areas in South Australia, Namibia, and Death Valley.

2. Establishing palaeo-ice sheet presence: the case for glaciation

Interpretation of the palaeoclimatological significance of IRD rests on not only establishing a convincing case for glaciation, but understanding its stratigraphic context within a glacial succession. The following features, structures and facies are very common in Sturtian successions in close association with IRD. Expectedly, not all are present in any one basin. Subglacial features, for example, will clearly be absent in a proglacial basin- and hence the absence of some also allows the basin context to be better understood.

(i) Striated pavements. These are rare in Sturtian successions, but are reported from South Australia (Young and Gostin, 1991) and Utah (Link et al., 1994). It may be that outcrop conditions simply preclude their recognition: subvertical strata characterise many South Australia sections (Busfield and Le Heron, 2014), whereas key sections in northern Namibia have dip angles of >45° (Hoffman and Halverson, 2008). Whilst such surfaces provide excellent evidence for warm-based grounded ice masses (Allen and Etienne, 2008), the case for glaciation cannot rest on discovery of such surfaces alone.

(ii) Subglacial soft-sediment deformation structures. Deposition and deformation of subglacial sediments are complex and modulated by hydraulic conditions (Menzies, 1989). Thin section study has

---

E-mail address: daniel.le-heron@rhul.ac.uk.

http://dx.doi.org/10.1016/j.sedgeo.2015.04.001
0037-0738/

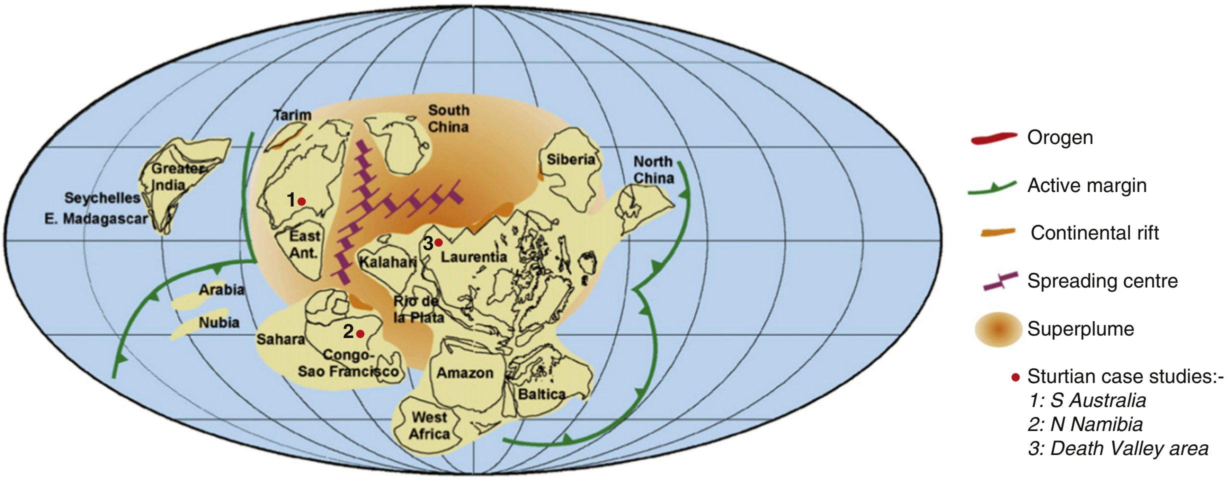

Fig. 1. Global palaeogeographic reconstruction at 720 Ma from Li et al. (2008), showing plate configuration at the time of the Sturtian glaciation. Glaciation was coincident with rifting of Rodinia (Eyles and Januszczak, 2004), here shown to be driven by a superplume. The locations of three sections which expose Sturtian deposits of outstanding quality in South Australia, Namibia and the Death Valley region of the USA are shown on the reconstruction.

revealed the microscale products and patterns of deformation (e.g., Hiemstra, 1999; van der Meer et al., 2003), and allowing subglacial shear zones to be recognised in successions (Busfield and Le Heron, 2013; Fleming, 2014) (Fig. 2A). For example, in the Chuos Formation of Namibia, intercalated ductile and brittle strain products are recognised (Busfield and Le Heron, 2013) (Fig. 2A), in close comparison to Pleistocene examples (Knight, 2015). At the meso-scale, debris flows characteristically move on a basal shearing layer, with the intensity of deformation diminishing upwards (Phillips, 2006); by contrast, subglacially-sheared sediments tend to exhibit an upsection increase in total strain. At the micro-scale, the upward decrease in deformation reported in debris flows (Phillips, 2006) can also be seen in subglacial tills at the meso (field) scale where the strain increases upsection, resulting in differential deformation at the base and fully homogenised from extreme deformation at the top (Benn and Evans, 1996). Based on Quaternary analogues, criteria to distinguish glaciomarine from glacitectonic deposits have been proposed by Hart and Roberts (1994). For comparison, in the Sturtian record, subglacial shear zones (glacitectonites; Evans et al., 2006) are commonly intercalated with deformed ice-rafted debris (e.g., Busfield and Le Heron, 2013). Outcrop conditions often favour the recognition of subglacial soft-sediment deformation structures, and hence they have a key role to play in establishing the grounding lines of Sturtian palaeo-ice sheets.

(iii) Deep palaeovalleys of subglacial origin. These exhibit highly variable fill styles, and are reported from Sturtian age outcrops in Oman (Kellerhals and Matter, 2003; Rieu et al., 2006) and Namibia (Hoffman and Halverson, 2008), ranging 1–400 m deep and 1–4 km wide. Subsurface examples are also recognised from the São Francisco Basin, Brazil, where they cut into downwarped pre-glacial strata (Bertoni, 2014; Bertoni et al., 2014) (Fig. 2B). The downwarping and deformation at the margins of the incisions imply ice loading, and are typical of tunnel valleys cut by meltwater into subglacial materials (Van der Vegt et al., 2012; Ravier et al., 2015). Palaeovalleys are typically onlapped by diamictite-bearing infill successions (Fig. 2C). The presence of palaeovalleys of the type described above implies their generation beneath a grounded ice mass.

(iv) Ice-marginal soft-sediment deformation structures. High amplitude (tens to hundreds of m) fold and thrust belts, or push moraines, occur in modern and Pleistocene ice marginal sediments (Schack Pedersen, 2005), allowing the location of the palaeo-ice margin to be proposed. Structures of a similar scale are reported from the Sturtian age Port Askaig Formation of Scotland on the island of Eileach an Naoimh (Fig. 2D). Spencer (1971) interpreted this as an ice-marginal deformation structure, but close association with an intraformational megabreccia led others to propose a downslope slumping mechanism (Arnaud and Eyles, 2002; Arnaud, 2004). The latter authors envisaged that this resulted from foundering of a glacially-influenced continental margin, underscoring the difficulty of confidently distinguishing ice-push structures from slump structures, although subsequent recognition of glacitectonites may add further credence to the ice-push hypothesis (see Benn and Prave, 2006). In sum, the recognition of ice-marginal deformation structures allows a palaeo-ice front to be deduced.

(v) Dramatic lateral facies changes. In ice contact settings, englacial conduits feed proglacial channels and their positions switch frequently (Brookfield and Martini, 1999). Thus, on a local scale, the switching position of point sources produces cut and fills both parallel and laterally across ice margins, contributing to the stratigraphic heterogeneity of glaciogenic deposits. In Sturtian strata, these are beautifully expressed in the Kingston Peak Formation of the Kingston Range, California, where thicknesses as well as facies changes occur along strike. Some of these changes are clearly attributable to syn-sedimentary fault activity and crustal extension (Prave, 1999; Macdonald et al., 2013). For example, in the Horsethief Spring area, coarse sandy turbidites abut against a series of en echelon faults that downstep into the basin (Le Heron et al., 2014a) (Fig. 3A, B). The satellite image and geological sketch map (Fig. 3A, B) clearly illustrate evidence for growth strata in this region. Elsewhere in the Death Valley region, evidence for fault-controlled thickness changes is well expressed in the Panamint Mountains (Miller, 1985) (Fig. 3C). To summarise, dramatic lateral facies changes often result from switching of point sources in ice-marginal environments but care must be taken to distinguish these from syn-sedimentary tectonic effects.

(vi) Diamictite textures at the meso-scale and micro-scale. As pointed out by Eyles and Januszczak (2004), diamictites of glacial origin can be deposited as debrites into proglacial basins. Debris flow deposits of both glacial and non-glacial character share similar characteristics, including abrupt lateral terminations (Iverson, 1997) and common inverse grading likely resulting from both kinetic sieving and upward clast migration (Legros, 2002; Benn and Evans, 2010; Talling et al., 2012). For stratified