A diamicite dichotomy: Glacial conveyor belts and olistostromes in the Neoproterozoic of Death Valley, California, USA

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ABSTRACT
Multiple intercalations of glacially derived and slope-derived diamicrites testify to the drawbacks of correlating Neoproterozoic diamicrites more widely, but shed new light on the close interrelationship of these processes in the Cryogenian world. In the Neoproterozoic of Death Valley, California (USA), rifting of Rodinia occurred concomitantly with a major glacial event that deposited the Kingston Peak Formation. A new sedimentologic investigation of this formation in the Silurian Hills demonstrates, for the first time, that some diamicrites are ultimately of glacial origin. Abundant dropstone textures occur in interstratified heterolithic deposits, with clasts of identical composition (gneiss, schist, granite, metabasite, quartzite) to those of boulder-bearing diamicrites suggesting a common source (the glacial conveyor belt). In stark contrast, megaclast-bearing diamicrites, yielding clasts of carbonate and siliciclastic preglacial strata as much as 100 m across, are interpreted as olistostromes. The occurrence of syn-sedimentary faults within the succession allows glacial versus slope-derived material to be distinguished for the first time.

INTRODUCTION
The distinction between diamicrites ultimately of glacial origin and those of mass flows derived from slope collapse is of fundamental paleoclimatic importance and has remained a prominent part of the research agenda in Neoproterozoic studies for over 50 yr (e.g., Schermerhorn, 1974; Eyles and Januszczak, 2004; Domack and Hoffman, 2011; Nascimento et al., 2016). Misinterpreting slope deposits as glacial, or vice versa, means that the number of glacial cycles in Earth’s history could be either under- or overemphasized (Arnaud and Etienne, 2011). Such an understanding is of profound importance in the Cryogenian, with putative palglacial (sensu Hoffman, 2009) episodes in the Neoproterozoic ~720–635 m.y. ago (Spence et al., 2016). In Death Valley (California, USA), the Kingston Peak Formation (KPF) was deposited in a regional sediment trap that received sediment from multiple directions (Mahon et al., 2014). A glacial influence has long been suspected (Hazzard, 1939). Mid-oceanic ridge basalt (MORB)–type pillow lavas on the western Death Valley flank (Labotka et al., 1980; Miller, 1985), en echelon growth faults in the Kingston Range (Walker et al., 1986), major lateral thickness variations (Prave, 1999), and olistostome complexes (Le Heron et al., 2014) all underscore the view that the sediments record glaciation superimposed on a rift event, or vice versa (Mrofka and Kennedy, 2011; Petterson et al., 2011). The Silurian Hills (SH) are one of the Death Valley outcrop belts that have received very little study in the past 40 yr. Their exposures yield critical insight into the competing influence of rift and glacial process in the Cryogenian. In the SH, Basse (1978) entertained two working hypotheses for the diamicite-bearing strata. The first was a mass-flow origin, supported by co-occurrence with repetitive turbidite deposits in the succession. The second was the contention that the deposits were glacimarine, but the absence of strong indicators for glacial deposition made this “inconclusive” (Basse, 1978, p. 51). In this paper, we resolve this controversy, with widespread implications for how rift-related and glacially related diamicites can be distinguished in the Cryogenian. The sections occur near the westward limit of the Basin and Range province and are cut through by a series of fault systems in multiple orientations that are well preserved throughout the succession. A new geological facies map of the KPF was deposited in a regional sediment trap that received sediment from multiple directions (Mahon et al., 2014). A glacial influence has long been suspected (Hazzard, 1939). Mid-oceanic ridge basalt (MORB)–type pillow lavas on the western Death Valley flank (Labotka et al., 1980; Miller, 1985), en echelon growth faults in the Kingston Range (Walker et al., 1986), major lateral thickness variations (Prave, 1999), and olistostome complexes (Le Heron et al., 2014) all underscore the view that the sediments record glaciation superimposed on a rift event, or vice versa (Mrofka and Kennedy, 2011; Petterson et al., 2011). The Silurian Hills (SH) are one of the Death Valley outcrop belts that have received very little study in the past 40 yr. Their exposures yield critical insight into the competing influence of rift and glacial process in the Cryogenian. In the SH, Basse (1978) entertained two working hypotheses for the diamicite-bearing strata. The first was a mass-flow origin, supported by co-occurrence with repetitive turbidite deposits in the succession. The second was the contention that the deposits were glacimarine, but the absence of strong indicators for glacial deposition made this “inconclusive” (Basse, 1978, p. 51). In this paper, we resolve this controversy, with widespread implications for how rift-related and glacially related diamicites can be distinguished in the Cryogenian. The sections occur near the westward limit of the Basin and Range province and are cut through by a series of fault systems in multiple orientations that are well preserved throughout the succession.

METHODS
A new geological facies map of the KPF in the SH (Fig. 1) was completed during two field seasons over 2015 and 2016. Most lithological boundaries on Kupfer’s (1960) map are extremely accurate, and thus our mapping is almost 1.4-km-thick succession (Fig. 2) (see the GSA Data Repository投资). Not all diamicrites are mappable; hence, the greater number of these are shown on the simplified sedimentary log than on the map.

DATA DESCRIPTION
Lonestone-Bearing Heterolithics Facies Association
The lonestone-bearing heterolithics facies association comprises normally graded sandstones and mudrocks, sandwiched between diamicrite intervals (Figs. 1 and 2). Lonestones in these strata have not historically been interpreted as dropstones: “the penetrative deformation criterion is not satisfied” (Basse, 1978, p. 51). However, careful reinvestigation by the authors found several examples of lonestones that do deflect and penetrate delicate underlying laminations and cross-laminae, and these are overlain by undeformed laminae. These are spread throughout the succession, first appearing 6 m above the base of the KPF (Fig. 3A), last appearing in the top 30 m of the formation (Fig. 3B), and appearing at multiple intervals in between (Fig. 2). They include gneiss, schist, granite, and quartzite pebbles and cobbles.

Boulder-Bearing Diamictite Facies Association
The boulder-bearing diamicite facies association comprises structureless clast-poor to clast-rich muddy diamicites. Clasts are subrounded to rounded and gneissose, schistose (Fig. 3C),
granitic, or quartzitic in composition. In stratigraphic section, uninterrupted 100-m-thick intervals of diamictite are recognized (Fig. 2). In some cases, diamictites show no trends in matrix character over such intervals, whereas in others, upward-coarsening and rare upward-fining patterns can be observed. At the meter scale, intercalation of diamictite beds with heterolithic, graded and rippled sandstones occurs (Figs. 2 and 3D). Most observed beds are massive, though rare occurrences of poorly stratified diamictites with wispy lamination (discontinuous, undulose bed partings) are noted.

Megaclast Diamictite Facies Association

Appraisal of both the map (Fig. 1) and the log (Fig. 2) shows that the megaclast diamictite facies association occurs at multiple stratigraphic levels. These intervals are typically >100 m each in thickness; some are fault-bounded (Fig. 1; see the Data Repository). They are characterized by megaclasts of orange dolostone (Fig. 3E), sandstone, and limestone, set within a black-weathering, locally folded (Fig. 3F) diamictite matrix. Rarely, above metabasite “sills” (Kupfer, 1960; Basse, 1978), clasts of metabasite of identical character occur within the megaclast diamictite facies association (Fig. 3G). Megaclasts are angular and measure up to 100 m in length (Fig. 1). Gneiss, schist, granite, and quartzite pebbles and cobbles are present, but only within intraclasts of the boulder-bearing diamictite facies association. At Rattlesnake

Figure 1. Geological facies map of Silurian Hills, Death Valley area, California (USA). Map was compiled over course of two field seasons from 2015 to 2016, with aim of differentiating boulder-bearing and megaclast-bearing diamictites. Map does not show member subdivisions, but rather details repeated intercalation of these two types of diamictites, thought to have been deposited through different processes.

Figure 2. Simplified sedimentary log throughout Kingston Peak Formation (California, USA). Color scheme and facies associations correspond to those shown on geologic map in Figure 1, but note that there is greater detail shown on log (i.e., some intervals on log are below mapping resolution or contain laterally discontinuous diamictites). Note abundance of ice-rafted debris (shown by dropstone symbol to right of log). Numbers and letters to right-hand side correspond to photos in Figure 3.
Ridge, bed thicknesses change across a series of normal faults; these faults are sealed by a thick package of the megaclast diamictite (Figs. 3H and 3H′; see also the Data Repository). This includes the largest megaclast in the SH (Figs. 1, 3H, and 3H′); previously interpreted as a Cambrian klippe (Basse, 1978), it is compositionally identical to orange dolostone and limestone clasts elsewhere in the succession.

DATA INTERPRETATION AND MODEL

The observation that gneiss, schist, granite, and quartzite clasts penetrate, puncture, and deform underlying laminae suggests that these clasts are dropstones. Moreover, the intercalation of these with delicately laminated and rippled deposits indicates that the clasts are hydrodynamically incongruent (i.e., were deposited by a different process than the encasing laminae; Le Heron, 2015). Multiple ice-rafted debris (IRD) intervals are thus recognized (Fig. 4). These textures, coupled with the graded beds described in detail by Basse (1978) and interpreted as turbidites, testify to a subaqueous origin (Fig. 4).

Allied to this, the boulder-bearing diamictite facies association is not considered to record primary ice-contact sedimentation (i.e., tillites), but rather debris-flow deposits. This interpretation carries an important caveat: the compositional similarity of the clasts in these debris to the dropstones, in tandem with their intercalation with IRD, strongly supports the suggestion that they are glaciogenic debris-flow deposits (GDFs) ultimately sourced from an ice sheet or glacier. While no striations on clasts are reported, comparison to a near-identical facies association some 30 km to the north at Sperry Wash (Busfield and Le Heron, 2016) shows that where the metamorphic grade is lower, delicate striations occur.

We offer a very different interpretation for the megaclast diamictite facies association. The highly angular nature of the megaclasts, predominantly composed of preglacial sedimentary material, suggests a local source and minimal transport. The assemblage bears close similarity to the olistostrome complex widely reported from the Kingston Range (Macdonald et al., 2013; Le Heron et al., 2014), and a similar mechanism is proposed here. The field evidence points to fault arrays that were active during deposition because thickness changes occur across the faults, and some fault arrays are sharply overlain by megaclast diamictites, some of which are themselves fault bounded (Figs. 1, 3H, and 3H′; see also the Data Repository). Therefore, unroofing and toppling of material from footwall blocks in the hinterland may well account for the size, shape, and composition of olistoliths (Fig. 4). This interpretation is strengthened by the concentration of metabasite clasts immediately above metabasite bodies, implying reworking of extruded igneous materials (rather than sill bodies as previously

Figure 3. Images of Kingston Peak Formation in Silurian Hills (California, USA). A,B: Lonestones, showing disruption and puncturing of underlying laminae beneath clasts. C: Cobble-sized clasts in boulder-bearing diamictite facies association. Visible clasts include gneiss and schist in this photograph. D: Boulder-bearing diamictite (hammer [33 cm long], for scale, circled) to left of photo, overlain by lonestone-bearing heterolithics to right of photo. E: Bright orange dolostone clast (hammer for scale, circled) to left of photo, overlain by lonoestone-bearing heterolithics to right of photo. F,G: Folded matrix to megaclast diamictite facies association (F) with metabasite clast (G) directly above the upper metabasite (hammer for scale). H,H′: Photo and line interpretation of megaclast diamictite facies association (i.e., olistostrome deposits) and relationships to en echelon faults, a metabasite (MB), and intercalated boulder-bearing diamictite (glaciogenic debris flow deposits). View is looking north (see Fig. 1 for location).

Figure 4. Simple model showing envisaged mechanisms to produce two dramatically different diamictite deposits in Death Valley (California, USA) area, focused specifically on Silurian Hills. First type (boulder-bearing diamictite) comprises glaciogenic debris flow deposits shed from ice margin and dominated by crystalline clast types. Second type (megaclast diamictite facies association) was produced by syn-sedimentary extensional faulting, yielding locally derived cover strata of preglacial stratigraphy, and locally metabasite. Intercalation of all these facies with turbidites and ice-rafted debris (IRD)—bearing heterolithics testifies to subaqueous sedimentation within basin.
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