A slippery slope for Cryogenian diamictites?

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Abstract
The Death Valley region has previously been claimed to preserve the sedimentary records of both the Sturtian and Marinoan snowball Earth events within the Kingston Peak Formation, which outcrops in a number of disconnected mountain ranges. In this context, new sedimentary logs are presented together with detailed clast textural analyses which allow diamictites of the Alexander Hills and the Saddle Peak Hills to be compared in detail for the first time, and to be contrasted with rocks of well-established glaciogenic origin from the Kingston Range. Notably, in the Saddle Peak Hills, clasts identical in composition and facies to that of the Noonday Dolomite—a unit previously interpreted as the post-Marinoan cap carbonate—are incorporated into diamictites at the top of the Kingston Peak Formation. Combined with the carbonate-rich composition of rocks at the top of the formation, these observations suggest that the uppermost diamictites of the Saddle Peak Hills and Alexander Hills are genetically related to the Noonday Dolomite and are unrelated to glacial processes. We propose that they formed through local slope foundering and basinward collapse of the adjacent carbonate platform, substantiating recent interpretations of Noonday carbonate platform dynamics, and demonstrating that they are genetically unrelated to Cryogenian glaciation. Thus, clast textural analyses play a valuable role in establishing whether contested ‘snowball Earth’ outcrops are truly glaciogenic or simply the product of local slope collapse.

KEYWORDS
Cryogenian, diamictite, glaciation, Marinoan, Neoproterozoic

INTRODUCTION
An understanding of the number of glaciations recorded in the global Neoproterozoic record is critical for two reasons. Firstly, under the Snowball Earth hypothesis, two global glaciations are postulated to have occurred during the Cryogenian Period (Hoffman, Kaufman, Halverson, & Schrag, 1998; Hoffman et al., 2017): in Death Valley, the rocks have been argued to archive both of these (Prave, 1999). Secondly, using this two glaciation paradigm, the strata of Death Valley have been used as a model to refine the Neoproterozoic tectonostratigraphy of the SW Laurentia margin as a whole, from California to Alaska (Macdonald et al., 2013).

Given this, distinguishing between diamictites of glacial versus slope origin in the rock record is a vital, yet often problematic, component of correct palaeoenvironmental and climate interpretations (Kennedy, Eyles, & Broughton, 2018; Letsch & Kiefer, 2017). This is especially true for Cryogenian
diamictites of Death Valley, which often record coeval glaciation and rifting (Eyles & Januszczak, 2004; Miller, 1985; Prave, 1999; Vandyk et al., 2018). In the Silurian Hills outcrop belt (Figure 1), Le Heron, Tofaif, Vandyk, and Ali (2017) proposed that diamictites ultimately of glacial origin were characteristically far travelled, typically comprising well rounded clasts from basement lithologies. This argument hinged on dropstones being compositionally identical to clasts within associated glaciogenic diamictites. By contrast, diamictites of slope origin were rich in highly angular megaclasts of basement cover material (typically foundered blocks of shelf dolostone), which are associated with growth faults, thus enabling differentiation from glacially-sourced materials. The present paper develops this analysis, focussing on the topmost part of the Kingston Peak Formation, across several Death Valley outcrop belts: the Saddle Peak Hills, Kingston Range and Alexander Hills. The aim is to use macro-fabric analysis to address two competing hypotheses, namely whether the uppermost diamictites are truly of glacial affinity, potentially representing the Marinoan glaciation in Death Valley (Macdonald et al., 2013), or whether they are genetically part of the overlying Ediacaran Noonday Formation, as has been recently proposed (Creveling, Bergmann, & Grotzinger, 2016). These findings are invoked to elucidate potential pitfalls of using stratigraphic context to discriminate between diamictites of glacial versus slope origin. Finally, comparison of the data herein is made to that of the interpreted Marinoan strata of the Panamint Range to explore whether they too may represent non-glacial slope deposits.

1.1 Geological setting and stratigraphy

Cryogenian diamictites occur in the Kingston Peak Formation of the Panamint Range, to the west of Death Valley (Peterson, Prave, & Wernicke, 2011), and in a suite of disconnected outcrops to the southeast of Death Valley (Le Heron, Busfield, Ali, Vandyk, & Tofaif, 2019). Key glaciogenic indicators comprise faceted, striated clasts and delicate dropstone textures, with local evidence for glaciotectonic deformation (Busfield & Le Heron, 2016 and references therein). In an influential paper, Prave (1999) proposed a tectonostratigraphy for the Death Valley region that recognized two periods of glaciation with coeval rifting, linked to the Sturtian and Marinoan glaciations, and overlain by an Ediacaran cap carbonate, the Noonday Formation (Peterson et al., 2011). This framework was later adapted by Macdonald et al. (2013), who assigned the Marinoan glaciation to a locally developed mapping unit in the uppermost Kingston Peak Formation, named KP4, and assigned all underlying glaciogenic strata to the Sturtian glaciation. In the Death Valley area, many exposures contain interbedded diamictites and ironstones. On geochemical grounds, ironstones interbedded with the Kingston Peak Formation diamictites are now considered unlikely to relate to rift-related hydrothermal activity as proposed for other localities (e.g. Cox et al., 2016) but rather to the production of oxygenated brines at the palaeo-ice margin (Lechte, Wallace, van Smeerdijk Hood, & Planavsky, 2018).

Macdonald et al. (2013) described and mapped KP4 in the Saddle Peak Hills, whereas in the Kingston Range they noted its presence but provided no description or indication of its location. In the uppermost Kingston Peak Formation of the southern Kingston Range, Le Heron, Busfield, Ali, Tofaif, and Vandyk (2018) described a diamictite, with striated clasts and stratified intervals containing limestones, intercalated with turbidites. They interpreted these deposits, including the diamictites, collectively as representing the upper part of a
subaqueous fan system in a proglacial setting that received ice-rafted sediment. This diamictite does not extend over the entirety of the southern Kingston Range and is locally absent (see fig. 5 of Lechte et al., 2018). In the Saddle Peak Hills, Creveling et al. (2016) described dropstone-bearing turbidites sharply overlain by polymict conglomerates (herein categorized as diamictites), marking the base of KP4. The clasts within these diamictites transition upwards from older Neoproterozoic lithologies of the underlying Pahrump Group, through clasts of the immediately underlying Kingston Peak Formation, to megaclasts (sensu Terry & Goff, 2014) of the Ediacaran Noonday Formation. Creveling et al. (2016) proposed two depositional scenarios, both invoking lowstand filling of submarine incised valleys either ‘Scenario 1’: KP4 was deposited prior to the Noonday Formation, supplied by glacial and/or alluvial processes. Importantly, KP4 in this interpretation only comprises the diamictite above the limestone-bearing turbidites but below the first appearance of Noonday megaclasts. By contrast, the Noonday megacaclast-bearing diamictite rests disconformably upon KP4 and represents an intra-Noonday Formation lowstand; or ‘Scenario 2’: KP4 comprises the full thickness of diamictite, from immediately above the dropstone-bearing turbidites to the overlying dololaminites of the Noonday Formation, including the Noonday megaclasts. This whole diamictite then represents the same intra-Noonday Formation lowstand deposit.

2 | METHODOLOGY

The uppermost diamictites of the Kingston Peak Formation were studied in three Death Valley outcrop belts by the authors during their 2017 field season, focussing on three localities (Figure 1): (a) the uppermost diamictite in the Saddle Peak Hills, including KP4 as described by Macdonald et al. (2013) and the overlying Noonday-megaclast-bearing diamictite (i.e. 6–48 m of section SP01 of Creveling et al., 2016, Figure 4); (b) mapping unit PCK4 of Wright (1974) in the Alexander Hills (Figure 2), reassigned to KP4 by Mrofka and Kennedy (2011); (c) diamictites previously interpreted as ‘glacial’ in the uppermost Kingston Peak Formation of the Kingston Range (Le Heron et al., 2018). In each of these areas detailed laterally equivalent sedimentary logs were completed, in particular focussing on clast lithology and morphology. Additionally, multiple 1 m² quadrats were placed at different stratigraphic levels over the outcrop, from which both lateral and vertical variation in clast composition and roundness, using Powers (1953) classification, were described. Quadrats were subsequently photographed and in the Alexander Hills only the PCK4 unit was remapped. For the quadrat analysis, the focus was placed on clasts in the range ø-4 to ø-8 on the Udden-Wentworth scale (i.e. coarse gravel to boulder-scale). Megaclasts (i.e. clasts greater in

**FIGURE 2** Geological map of the Alexander Hills, adapted from Wright (1974). The only modification is the boundary of unit pCK4.
size than ϕ-8; see Terry & Goff, 2014) were noted and described, but excluded from the quadrant analysis. The clast textural analysis was undertaken in the field (i.e. roundness and lithology were described at outcrop). Although recent work has highlighted the use of micromorphology/thin section analysis to describe and interpret Cryogenian diamicrites (Busfield & Le Heron, 2018), this methodology was considered unsuitable for our study sections. Owing to the high carbonate content of the outcrops in the Saddle Peak Hills and Alexander Hills, grain-boundary dissolution and stylolitization adversely affects textures in thin section.

3 | RESULTS

3.1 | Saddle Peak Hills: Descriptions

In the western part of the Saddle Peak Hills the uppermost diamicite is up to 30 m thick and rests disconformably upon repetitively-bedded, ferruginous turbidites that bear occasional limestones (Figures 3a, 4 and 5a). These latter rocks are very similar to the well-studied succession exposed a few kilometres to the east at Sperry Wash (Busfield & Le Heron, 2016). The diamicite expresses a well-developed coarsening upward, in terms of maximum clast size, with the majority of Noonday Formation megaclasts concentrated in the upper 10 m (Figures 4 through 6). It is conformably overlain by dololaminites of the Noonday Formation (Figure 5a–c). The uppermost part of the megaclast-bearing diamicite is dominated by lath-shaped, pencil-shaped and generally oblately-shaped dololamine clasts of identical composition to the overlying, undisturbed, dololaminites (Figure 5b,c). Panoramic views of the megaclast-bearing diamicite (Figure 5a) reveal that the megaclasts exhibit a spectrum of rounded, equant shaped to angular, slab-like morphologies. Some of the latter include sub-angular clasts representing part of a Bouma sequence resembling the underlying Kingston Peak Formation (Figures 3a and 6a). However, the majority of the megaclasts comprise carbonate (Figures 3a and 6b), some with highly distinctive features typical of cap carbonates (Creveling et al., 2016; Shields, 2005), including folded and deformed dololamine clasts of identical appearance to the overlying Noonday Formation (Figure 6c: compare with Figure 5b) and pipe-like features (Figure 6d).

Within the quadrats, carbonate clasts (Figure 5d) are dominant and comprise 98% of the 208 clasts recorded (Figure 7), although not all are identifiable of Noonday Formation origin, whereas sandstone (Figure 5e) and mudstone clasts are rare. They also reveal that highly irregular clast shapes are common, with 92% classified as angular or very angular using Powers (1953) roundness scale (Figure 7c). Neither the quadrats nor measured sections (excluding megaclasts) suggest that there is an upward change in the dominance of carbonate clasts or their angular character.

3.2 | Alexander Hills: Descriptions

This region was mapped by Wright (1974), who divided the Kingston Peak Formation into mapping units pCK1–pCK4, later reassigned as KP1–KP4 by Mrofka and Kennedy (2011). The reader is referred to Le Heron et al. (2019) for a review of this issue. The map presented herein (Figure 2) only slightly modifies the earlier work of Wright (1974). In detail, the boundary of the uppermost Kingston Peak Formation diamicite, pCK4, now forms a wedge-shaped geometry that pinches out to the north and terminates against the Sheephead fault to the south. This unit comprises megaclast-bearing diamicite in which multimetre-sized clasts are set within a ‘matrix’ of pebbly to boulder-rich diamicite (Figures 8d,e and 9). It occurs immediately above graded sandstones of pCK3 (Figure 8c), very similar to those beneath KP4 of the Saddle peak Hills, although the contact between these units is typically concealed. On Figure 8d, for example, the geologist is standing on ferruginous graded beds (pCK3), exposure immediately above is patchy and large orange and brown megaclasts (pCK4) up to 6 m in diameter crop out further up the cliff section. Beneath these sandstones are boulder-bearing diamicitics of unit pCK2, within which clasts are more rounded than pCK4 and no megaclasts occur (compare Figures 8b and 9). Panoramic photographs illustrate that some of the megaclasts are arranged as trains of multi-metre scale blocks, for example four brown megaclasts left of ‘E’ in Figure 8a. These are encased within a predominantly silty, red-coloured, and highly heterogeneous matrix (Figure 8e).

In the Alexander Hills, the quadrant analyses reveal that highly irregular boulder and cobble clasts are commonplace, representing the ‘matrix’ to the megaclast-bearing diamicite. There are several examples of adjacent clasts arranged like the pieces of a jigsaw puzzle (Figures 3b, log ii and 9a). In terms of clast count (Figure 9b), whilst broadly comparable to the Saddle Peak Hills in terms of a dominant carbonate clast composition (93%), there is a slightly greater proportion of sandstone clasts (6%). Using Powers (1953) index, some 76% of studied clasts are either angular or very angular, with only 1% described as rounded (Figure 8c). As in the Saddle Peak Hills, there is no clear stratigraphic trend in these characteristics.

3.3 | Southern Kingston Range: Descriptions

The southern Kingston Range has been the subject of considerable recent detailed investigation, including detailed sedimentary logging through the full 2.5 km thickness of the Kingston Peak Formation (Le Heron et al., 2018). In a similar manner to the Saddle Peak and Alexander Hills areas, a thick (40 m) diamicite-dominated package appears in the
**Saddle Peak Hills sections**

- Fig. 7A(v)
- Fig. 6A–E

- Fig. 4

- Fig. 7A(iii)

- Fig. 7A(ii)

**Alexander Hills sections**

- Fig. 9A(i)
- Fig. 9A(ii)
- Fig. 9A(iii)
- Fig. 9A(iv)
- Fig. 8A

**Southern Kingston Range section**

- Fig. 11A(i)
- Fig. 11A(ii)
- Fig. 11A(iii)

**Facies associations**
- Carbonate
- Pebble to boulder conglomerate
- Lonestone-bearing
- Interbedded heterolithics
- Boulder-bearing diamictite
- Megaclast-bearing diamictite

**Sedimentary structures**
- Parallel lamination
- Unidirectional cross-lamination
- Bladed clasts
- Load casts
- Trough cross-bedding
- Intrabed folds
- Mud clasts

**Lithologies**
- Conglomerate
- Diamictite
- Sandstone
- Mudrock
- Mudrock with dropstones
- Dolostone
stratigraphy immediately below the Ediacaran Noonday Dolomite and above a series of graded beds (Figure 3c). This diamictite is punctuated by lenticular bedsets of graded conglomerate, graded sandstone and mudstone (Figure 10a). Sharp contacts separate the typically brown-red graded beds from the typically green diamictites (Figure 10b). Unlike the Saddle Peak and Alexander Hills, these diamictites vary between massive and stratified varieties (Figure 10c). Excellent examples of limestones occur both in mudstones found between graded sandstone beds (Figure 10d) and within the stratified diamictites (Figure 10e).

Quadrat analysis of the upper diamictite in the Kingston Range (Figure 11) illustrates that the clast populations are more heterogeneous than their counterparts in the Saddle Peak or Alexander Hills. Particularly notable are large clasts of metabasite in the study area (Figure 11a): very similar to metabasites forming megaclasts further down the succession (Le Heron et al., 2018), derived from a 1.08 Ga diabase intrusion into the Crystal Spring Formation (Calzia et al., 2000; Heaman & Grotzinger, 1992; Vandyk et al., 2018). In terms of clast populations, whilst dolostone is the dominant lithology (62%) and sandstone accounts for almost a quarter (23%) of described clasts, metamorphic clasts (schist and gneiss) make up 8% of the 313 counted clasts (Figure 11b). By further contrast with the Saddle Peak and Alexander Hills sections, 73% of clasts classify as rounded and well-rounded on Powers (1953) scale: only 2% are angular and there were no very angular clasts observed (Figure 10c).

4 | INTERPRETATIONS

In the Saddle Peak Hills, diamictites and their clasts form the ‘matrix’ in which megaclasts of the Kingston Peak and Noonday formations occur. Despite the restriction of Noonday megaclasts to the upper third of these diamictites, the quadrats reveal that there is no clear up section change in the clasts within this ‘matrix’—carbonate clasts remain dominant at all stratigraphic levels, as does their strikingly angular character. The concentration of Noonday megaclasts in the upper 10 m suggests dispersive pressures within a debris flow, possibly in concert with kinetic sieving (Creveling et al., 2016). The lath-shaped, pencil-shaped and oblately-shaped dololaminite clasts testify to very low transport distances and most likely
steep slopes at a basin margin. The occurrence of angular blocks of material, derived from the graded beds immediately beneath the ‘KP4’ unit, suggests that slope failure involved the Kingston Peak Formation as well as the evolving carbonate platform. The folding of these blocks is interpreted as having occurred in soft sediment, suggesting only partial lithification. This might imply that only a limited period of time separated deposition of the glaciogenic turbidites of the Kingston Peak Formation and the overlying carbonate deposits of the Noonday Formation. It is worth noting that Creveling et al. (2016) envisaged upsection changes in the composition of the ‘KP4’ unit based on megaclasts. No clear upsection changes in ‘KP4’ are recognized herein, and yet this does not necessarily contradict their findings. This is because the quadrat analysis employed here focussed on material with a maximum size of ø-8 (boulders), corresponding to the ‘matrix’ of a megaclast-bearing diamictite.

In the Alexander Hills, it can be speculated that because the thickest occurrence of the pCK4 succession abuts against the major NW–SE striking Sheephead Fault and pinches

**FIGURE 5** Stratigraphic and sedimentological features of the uppermost Kingston Peak Formation in the Saddle Peak Hills. (a) View of the section straddling the uppermost Kingston Peak Formation and the Noonday Formation above. Geologist (circled) is standing on recessive diamictites. Strata are dipping approximately 40°E (to the left in the direction of view). To the left of the geologist, note the large buff coloured megaclasts of dolostone, which are concentrated in the uppermost 5 m of the Kingston Peak Formation. The Kingston Peak Formation is concordantly overlain by dololaminite of the Noonday Dolomite. (b) Detailed view of the saddle in the midground of photograph (a). The walking pole rests on highly brecciated material almost entirely made up of bladed, prolate clasts of dololamine: undisturbed (i.e. unbrecciated) dololamine of the Noonday Dolomite, consisting of laminae of identical composition to those of the brecciated material beneath, lie just above the top of the walking pole. (c) View of the contact described for photo (b) in detail. (d) The contact between the Kingston Peak and Noonday Formations next to the walking pole in photograph (b). Note that clasts are exclusively dolostone, which themselves are dominantly dololaminites. (e) Detail of recessive diamictites next to the geologist’s foot in photo (a). Whilst dominated by highly angular clasts of dolostone, other sedimentary clasts are also present, including two sandstone pebbles just to the left of the coin.
out to the north, this deposit derives from palaeo-fault movement, with the deposits recording accumulation on the hangingwall. About 10 km to the NE, well-established syn-sedimentary fault scarps crosscut the Kingston Peak Formation (Walker, Klepacki, & Burchfiel, 1986): a major olistostrome complex was shed from these extensional fault arrays (Le Heron, Busfield, & Prave, 2014). Likewise, pronounced lateral thickness variations in the Kingston Peak Formation of the Panamint Range attest to syn-depositional tectonics (Miller, 1985). Thus, there is a precedent of ‘sudden’ appearance of megaclast-bearing material, and associated dramatic lateral thickness changes, adjacent to major fault systems in Death Valley, which demonstrates a structural control on sedimentation. It therefore appears that the E–W striking fault crosscutting the outcrop was active during Kingston Peak Formation time. Texturally, all evidence also points to a local origin via a collapsing carbonate platform, in a similar manner to the Saddle Peak Hills sections, rather than to a possible glacial deposit (Prave, 1999). Whilst sandstone clasts are common, dolostone clasts remain dominant in the quadrat analysis performed here, and the predominance of angular to very angular clasts suggests, by direct comparison to the Saddle Peak Hills (Creveling et al., 2016), a very local source, probably as a result of toppling of material over a fault scarp into the basin. It is argued here, therefore, that the pCK4 unit is ‘an olistostrome in miniature’, implying local derivation and fault control, by reference to studies of the Kingston Peak Formation in neighbouring ranges (Le Heron et al., 2014, 2017).

By contrast with the Saddle Peak and Alexander Hills rocks, which are interpreted as unrelated to glaciation, the diamicites at the top of the Kingston Peak Formation in the southern Kingston Range are interpreted as glacially derived. The arguments revolve around (a) the presence of
glacial indicators in interstratified graded beds and mudstones, (b) textural considerations and (c) clast population heterogeneity. With regard to the first point, Le Heron et al. (2018) point out the occurrence of lonestones that down-warp laminations in stratified diamictites, and thus posit an origin via ice-rafting. The massive diamictites, by contrast, were viewed by those authors as a refluxed variety of this facies (glaciogenic debris flows). Additional evidence for a glacial origin lies in the occurrence of striated clasts, together with the much broader range of clast lithologies. The agent for transporting clasts over long distances was, in the case of the upper diamictite in the southern Kingston Range, the glacial conveyor belt. There is one aspect to the interpretations which stands in stark contrast with general assumptions about textures predicted in ancient glacial sediments. The observation that some 73% of the clasts studied in the Kingston Range quadrat analysis are rounded to well-rounded is perhaps counter-intuitive, but can be understood in terms of recycling of clasts both through englacial, sub-glacial and proglacial processes. In other glacial records, rounded but beautifully striated clasts are very commonplace because they record several generations of recycling (Tofaif, Le Heron, & Melvin, 2019).

5 | DISCUSSION

In each of the Death Valley outcrop belts studied, the uppermost Kingston Peak Formation consistently comprises graded beds overlain by diamictite, capped by dololaminites of the Noonday Formation. However, it is possible to argue that these similarities in general facies, stratigraphic context and stratigraphic position are in themselves insufficient to assign tectonostratigraphic or chronostratigraphic significance to these units. Neither in the Saddle Peak nor in the Alexander Hills does the interpretation presented here suggest that the uppermost diamictites are glaciogenic. Conversely, in the southern Kingston Range there is support for the previous interpretation of a glaciogenic affinity (Le Heron et al., 2018).

Despite the operation of comparable depositional processes in the Saddle Peak and Alexander Hills, coupled with apparently identical stratigraphic context and position, caution should be employed against any assumption that the two were deposited coevally. The idea that megaclast-bearing diamictites are locally derived and result from
carbonate platform collapse, perhaps involving major faults in the Alexander Hills, has previously been suggested in the Kingston Range (Walker et al., 1986) and Silurian Hills (Le Heron et al., 2017). Moreover, it is widely accepted that Precambrian syn-sedimentary faults within the Kingston Peak Formation record the rifting of Rodinia (Le Heron et al., 2017).
et al., 2017; Mahon, Dehler, Link, Karlstrom, & Gehrels, 2014; Macdonald et al., 2013; Prave, 1999; Walker et al., 1986). During rifting, time-transgressive evolution of fault systems (Alves et al., 2009; Eyles & Januszczak, 2004) would be expected at the margins of the Death Valley basin, and thus correlating deposits laid down in the lee of degrading fault scarps is fraught with difficulty. Nevertheless, there is one scenario wherein the locally derived megaclast-bearing diamictites of the Saddle Peak and Alexander Hills might be broadly time-equivalent and genetically related. In the central Kingston Range, Le Heron et al. (2014) posited that a major olistostrome complex in the middle of the Kingston Peak Formation may have been emplaced during interglacial isostatic rebound. Glacioisostatic rebound was also entertained as a viable scenario by Creveling et al. (2016), for the uppermost diamictites in the Saddle Peak Hills, and it is proposed that this mechanism can extend to the pCK4 unit in the Alexander Hills. However, in this model,

**FIGURE 9** (a) Selection of 1 m² quadrats from the upper Kingston Peak Formation in the Alexander Hills. Original photographs of the rocks are shown alongside their interpreted counterparts. See Figure 3 for stratigraphic position. (b) A pie chart representing all the clasts shown in the quadrats by % clast type. (c) A pie chart representing all the clasts by texture according to Powers (1953) roundness scale.
pre-existing faults may have been reactivated during or following retreat of the Kingston Peak Formation ice sheets, in a manner similar to the ‘piano-key tectonics’ envisaged for Pleistocene glaciated basins (Eyles & McCabe, 1989). It is therefore more likely that rebound-related deposits were diachronous, underscoring the argument that they have...
scant chronostratigraphic value. Absolute age constraint from within the Kingston Peak Formation cannot resolve this issue, as there are no syn-depositional ages and the youngest maximum depositional ages are Mesoproterozoic (Mahon et al., 2014; Vandyk et al., 2018). In the Valjean Hills, Mrofka and Kennedy (2011, p. 453) also noted that ‘Noonday Dolomite clasts are included in diamictite of the KP4 member or are in diamictite interbedded with KP4 member sedimentary breccia’, suggesting that the model proposed herein can also be extended to those sections, although further work to establish this is required.

The uppermost diamictites of the Saddle Peak and Alexander Hills, with their megaclasts derived from slope failure, can be considered modest examples of olistostromes. In this context, their diachronous emplacement by slope failure is well preceded within stratigraphically lower parts of the Kingston Peak Formation. For example, one olistostrome occurs in both the Goler Wash of the Panamint Range (Prave, 1999) as well as in the central and southern Kingston Range (Figure 1; Calzia et al., 2000; Le Heron et al., 2014; Macdonald et al., 2013). The southernmost Kingston Range exposes by far the thickest Kingston Peak Formation outcrop in the entire Death Valley area, and would presumably therefore be expected to contain the most complete sedimentary archive (Le Heron et al., 2018). Despite this, the Silurian Hills succession is thinner yet has four olistostrome intervals, generally <300 m thick, with megaclasts of both carbonate and metabasite (Le Heron et al., 2017). Regionally, the different number of olistostrome intervals strongly suggests that basin-bounding faults operated diachronously from outcrop belt to outcrop belt, undermining their use as chronostratigraphic markers.

Le Heron et al. (2017) noted the angular character and dominance of locally derived clast-types in the Silurian Hills and was able to use these criteria to distinguish slope-failure from glacial deposit. This same difference in clast composition and

FIGURE 11  (a) Selection of 1 m² quadrats from the upper Kingston Peak Formation in the southern Kingston Range. Original photographs of the rocks are shown alongside their interpreted counterparts. See Figure 3 for stratigraphic position. (b) A pie chart representing all the clasts shown in the quadrats by % clast type. (c) A pie chart representing all the clasts by texture according to Powers (1953) roundness scale.
angularity also distinguishes the uppermost diamictites of the Saddle Peak and Alexander Hills from those of glacially derived diamictites of the Kingston Range. Importantly, this suggests that these criteria may be used to distinguish slope-failure from glaciogenic diamictites elsewhere in the region. The remainder of this section uses this concept to consider whether the Marinoan glaciation is represented in the Panamint Range and therefore in the Death Valley region at all.

The two-glaciation stratigraphic framework established in the Death Valley region (Miller, 1983, 1985; Prave, 1999) has played an important part in the subsequently developed tectono-stratigraphy of the SW Laurentian margin (Macdonald et al., 2013; Yonkee et al., 2014). It originated in the Panamint Range, where the uppermost diamictite—the Wildrose submember (Miller, 1987)—has been interpreted as representing the Marinoan glaciation on account of its erosional, unconformable base and position above a Sturtian cap carbonate (Sourdough Limestone; Macdonald et al., 2013; Prave, 1999). However, the problem of distinguishing between Ediacaran slope-failure and glaciogenic debris flows is equally pertinent for these strata as it is for the Saddle Peak Hills (Creveling et al., 2016; Miller, 1987). The Wildrose diamictite shares key features with the slope-failure diamictites of the Saddle Peak and Alexander Hills (Miller, 1987): (a) a down-cutting erosional base, reworking underlying material; (b) carbonate megaclasts up to 3 m in length, including angular clasts resembling the Noonday Formation; (c) structureless diamictite, with rare clast trains; (d) uneven distribution, only locally developed; and (e) complete lack of direct glacial indicators such as striated clasts, dropstones or subglacial deformation. Added to this there is the suggestion that this diamictite interfingers with the Noonday Formation, precluding a glaciogenic interpretation (Miller, 1987): (a) continuous Wildrose diamictite beds, about 15 m thick, overlie the Noonday Formation in Tuber and Upper Wildrose Canyons; (b) Wildrose diamictite lenses within the basal Noonday Formation occur at these localities and South Park, Big Horn and the Redlands Canyon; (c) Wildrose diamictite cuts down through the Noonday to rest upon older strata of the Kingston Peak Formation at Surprise Canyon (Miller, 1987, Figures 2 and 6). This similarity to the Saddle peak and Alexander Hills, combined with its stratigraphic context, might suggest that the Wildrose diamictite represents carbonate platform collapse and that the Marinoan glaciation is absent from the Death Valley region. Miller (1983) provided clast-count data from 23 different examples of the Wildrose diamictite, which, by comparison to the data presented herein, can be used to test this hypothesis.

The compositional heterogeneity of clasts from the Wildrose diamictite (Figure 12) draws closer comparison to the Kingston Range uppermost diamictites, than the slope-derived deposits of the Saddle Peak Hills or the Alexander Hills. Carbonate clasts are common (34%), but quartzite is dominant (40%), and a range of other clast types (granites: 13%; gneiss: 3%; diabase: 1%) are also present. There is considerable variation between samples of the same section, for example at Goler Wash quartzite clasts vary from 28% to 81% (GW592, GW594), which is a feature of the Kingston Range but not the Saddle Peak or Alexander Hills diamictites (cf. Figures 7, 9 and 11). These clast-count data support the suggestion of Prave (1999) that the carbonate with which the Wildrose diamictite interfingers is in fact the Cryogenian ‘un-named’ limestone and not the Noonday Formation. Prave (1999) noted differences in lithology between the un-named limestone and the Noonday Formation in the Surprise Canyon, despite Miller (1983, 1985, 1987) stating they are alike. Furthermore, the carbon isotope values of the un-named limestone, around 6‰ (n = 3), is unusually heavy for a cap carbonate. In summary, a non-glaciogenic slope-failure source cannot be ruled out for the Wildrose submember. However, if the clast compositional data are interpreted similarly to the sections from the Saddle Peak Hills and the Alexander Hills, then a glacial origin also remains possible. Further investigation is required to resolve this question.

**6 | CONCLUSIONS**

Reappraisal of diamictites in the uppermost part of the Kingston Peak Formation, Death Valley, reveals that
some deposits previously allied to the Marinoan glaciation are non-glacial in character. These deposits, which are exposed in the Saddle Peak and Alexander Hills, represent material that is derived from the immediate area and was produced through carbonate platform collapse events. Clast counting, not including megaclasts, reveals a dominant (>90%) dolostone component, with the vast majority of clasts classified as angular to very angular on Powers (1953) roundness chart, which does not change up-section. In the Saddle Peak Hills, this lack of change reinforces the idea that the KP4 diamictite of Macdonald et al. (2013) is genetically related to overlying diamictite containing megaclasts of foundered Noonday Formation cap carbonate. In the Alexander Hills, there is equally little reason to interpret the uppermost diamictite as glacially derived. Nevertheless, the likely diachronous nature of both rifting and/or deglacial uplift conspire to prevent chronostratigraphic links being made between the uppermost Saddle Peak and Alexander Hills diamictites. By contrast, analysis of a diamictite section at a comparable position to the slope-deposits of the Saddle Peak and Stratified diamicite, underscores their glacial affinity. In the latter area, (a) the greater variety of clast-types is supportive of a wide-ranging provenance area typical of glacially transported debris, and (b) the greater degree of roundness of the clast population is suggestive of several generations of reworking rather than local slope collapse followed by deposition. These clast characteristics are shared by the Wildrose submember, which purportedly represents the Marinoan glaciation in the Panamint Range, west of Death Valley. On this basis, despite its similarities in general facies, stratigraphic context and stratigraphic position to the slope-deposits of the Saddle Peak and Alexander Hills, a glacial interpretation is supported for the Wildrose diamictite. It has been demonstrated herein that coincidence of stratigraphic context and general facies type between outcrops is, in the case of diamictites, insufficient to demonstrate either coeval deposition or a glacial affinity. Instead alternative lines of evidence, such as clast-count data, should be used to verify such assumptions, which in this case have cast considerable doubt as to whether the Marinoan glaciation may be recognized in the SE Death Valley region.

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CONFLICT OF INTEREST

There are no conflicts of interest in the preparation or publication of this work.

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