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Deep valley incision in the terminal Neoproterozoic (Ediacaran) Johnnie Formation, eastern California, USA: Tectonically or glacially driven?

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Abstract

Neoproterozoic sedimentary successions worldwide display evidence for multiple low-latitude glacial events and continental rifting episodes related to the fragmentation of the supercontinent Rodinia. In Death Valley, eastern California, these events are represented by two intervals of glacial diamictite and two episodes of synsedimentary extensional faulting in the Kingston Peak Formation. Deep incised valleys of uncertain origin in the upper Johnnie Formation, approximately 1 km stratigraphically above the Kingston Peak Formation, may provide evidence either for a third glacial episode or for an additional tectonic event. Eleven measured sections indicate that one of these incised valleys is 120 m deep and approximately 2.5 km wide. Detailed mapping of the paleovalley has revealed the presence of numerous synsedimentary normal faults that offset underlying units but are capped by incised valley breccia. Abrupt incision occurs across buried normal fault scarps. Several large olistoliths (up to 15 m in diameter) are located near the fault scarps and the average clast size of the breccia decreases in general away from mapped normal faults. Incised valley clasts are derived exclusively from underlying Neoproterozoic formations, nearly entirely from the Johnnie Formation itself. There is no evidence for direct glacial influence as no striated clasts or dropstones were observed. The absence of glacial indicators coupled with the strong correlation between incision and synsedimentary normal faulting imply a primary tectonic control on valley formation. The valley represents a significant tectonic reactivation of the Neoproterozoic passive margin, similar to early Paleozoic extensional events in the northern Cordillera of western North America.

Keywords: Ediacaran; Incised valley; Extensional tectonics; Johnnie Formation; Tectonic reactivation

1. Introduction

The Neoproterozoic was a time of extreme environmental change, including multiple extensive glacial episodes (Hoffman and Schrag, 2002; Kaufman et al., 1997; Kennedy et al., 1998) and the protracted fragmentation of the supercontinent Rodinia (Dalziel, 1991; Hoffman, 1991; Moores, 1991). Despite the fundamental importance of these events, the number and timing of "snowball Earth" glaciations and details of the tectonic history of Rodinia breakup remain controversial. Although an increasing number of Neoproterozoic glacial deposits have been dated directly (Bowring et al., 2003; Calver et al., 2004; Fanning and Link, 2004; Hoffmann et al., 2004; Lund et al., 2003), the age and correlation of many glaciogenic units, including those in the southwestern United States, are unknown, hindering our understanding of extreme climatic fluctua-

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tions during the Neoproterozoic. Likewise, Laurentia is thought to have occupied a central position within Rodinia, but complexities in the rift history of western North America (Colpron et al., 2002; Lund et al., 2003) have made detailed contintental reconstructions controversial (Brookfield, 1993; Moores, 1991; Sears and Price, 2003). Because of the central position of Laurentia in Rodinia and the importance of precisely correlating "snowball Earth" glaciations, a detailed understanding of the glacial and rift history of western North America is crucial for interpretations of Neoproterozoic climate and tectonics.

In the southern Great Basin, centered in the Death Valley region of eastern California, the Neoproterozoic succession contains clear evidence for at least two episodes of glaciation and extensional tectonism (Fig. 1), recorded by thick diamictite units of the Kingston Peak Formation, followed by development of the Cordilleran passive margin during deposition of the Noonday Dolomite (Prave, 1999). This history is similar to many other sections in the North American Cordillera and worldwide, which also contain two glacial intervals (Kennedy et al., 1998), and to other Cordilleran localities, which also display evidence for two rifting events (Colpron et al., 2002). However, additional evidence for glaciation and/or tectonism may exist in the Rainstorm Member of the stratigraphically higher Johnnie Formation, which contains incised valleys of uncertain origin exposed in the Panamint Mountains, Nopah Range, and Resting Springs Range (Fig. 2), some as deep as 120 m (Summa, 1993). On the one hand, the incised valleys previously have been related to glacioeustacy, and thus, linked to one of the Neoproterozoic glacial episodes (e.g., Abolins et al., 2000). If the incised valleys are glacioeustatic in origin, then the Death Valley region is unusual in recording three unequivocal "snowball" glacial episodes (cf. Xiao et al., 2004) and can help refine models for climatic fluctuations in the Neoproterozoic. Alternatively, a tectonic origin for the incision (e.g., Summa, 1993) may imply that the history of continental rifting in the southern Cordillera was more complicated than previously thought, with possible implications for the tectonic evolution of western North America and the breakup of the supercontinent Rodinia. Potential correlation with incised valleys at broadly similar stratigraphic position in Idaho and Utah (Christie-Blick and Levy, 1989; Levy et al., 1994), northwestern Canada (Dalrymple and Narbonne, 1996), and South Australia (Christie-Blick et al., 1995, 1990; Williams and Gostin, 2000) may strengthen the argument for a glacioeustatic origin. However, direct sequence stratigraphic correlation is highly tenuous in the absence of robust biostratigraphic or chronomet-

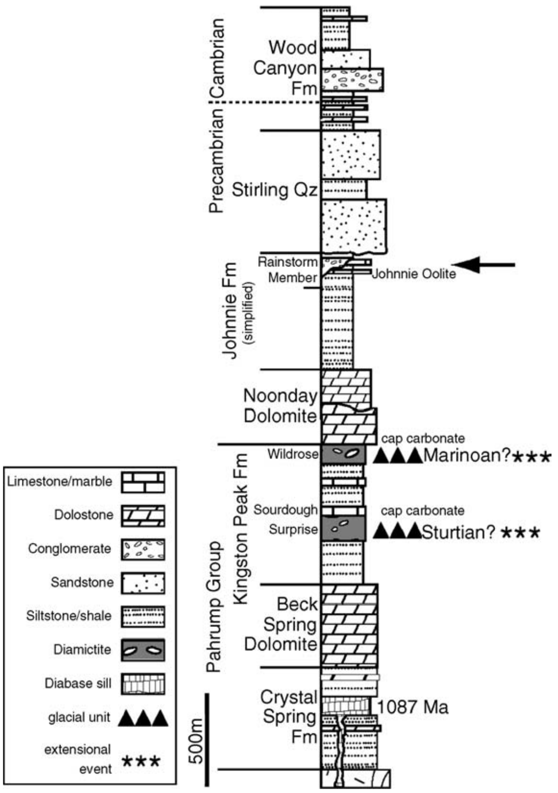

Fig. 1. Simplified composite stratigraphic section of Neoproterozoic units in the Death Valley region. Stratigraphic position of rift events indicated by asterisks and glaciations by triangles. Age constraints from Heaman and Grotzinger (1992). Studied incised valley is denoted by the arrow in the upper Johnnie Formation.

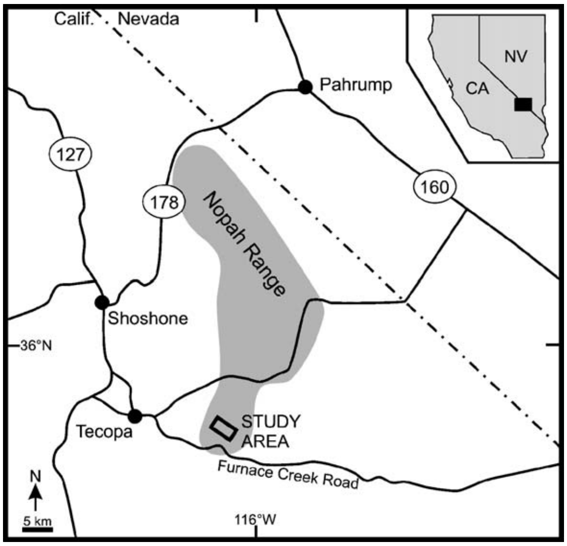

Fig. 2. Location map showing study area in the southern Nopah Range, eastern California.

ric control, and the potential linkage between Australia and Laurentia in the Neoproterozoic (Brookfield, 1993; Dalziel, 1991) suggests that similar-aged incision (e.g., Wonoka canyons) on both continents may instead represent a shared tectonic history (e.g., Williams and Gostin, 2000). Alternatively, the incision could simply reflect an additional complexity in the protracted rift history of western Laurentia (Colpron et al., 2002; Lund et al., 2003). Here, we examine the detailed stratigraphic context of a particularly well-exposed example of the Rainstorm Member incised valleys, located in the southern Nopah Range, documenting the valley fill, structure, and incision in order to test the relative influences of glaciation and/or tectonics in its formation.

2. Geologic background

The Neoproterozoic succession in the western Great Basin contains abundant evidence for "snowball Earth" glaciations and extensional tectonism (Fig. 1), represented by the diamictites and "cap carbonates" of the Kingston Peak Formation and Noonday Dolomite (Corsetti and Kaufman, 2003; Prave, 1999). The Kingston Peak Formation contains evidence for two pulses of glaciation, each overlain by a cap carbonate that records negative $\delta^{13}C$ values. In the Panamint Range, oldest glacial deposits are represented by the Surprise diamictite member, which contains, among other lithotypes, abundant iron-rich, dropstone-laden turbidites (Miller, 1982). The Surprise diamictite is overlain by the Sourdough Limestone cap carbonate (Prave, 1999). The Wildrose member, a second glacial unit and the uppermost unit in the Kingston Peak Formation, is in turn overlain by the Noonday Dolomite cap carbonate. The depositional age of the succession is loosely constrained between 1.08 Ga (Heaman and Grotzinger, 1992) and 543 Ma (Corsetti and Hagadorn, 2000) by radiometric and biostratigraphic data. However, sedimentological and chemostratigraphic evidence, including the presence of iron formation (Corsetti and Kaufman, 2003), suggests that the older Surprise diamictite and Sourdough cap are likely equivalent to the older, iron-rich glacial sediments found throughout western North America (e.g., the Rapitan Group in northwest Canada). The younger Wildrose diamictite and overlying Noonday cap carbonate then represent a younger event of unknown age; they may be correlative to 685 Ma (Lund et al., 2003), 635 Ma (Hoffmann et al., 2004), or 580 Ma (Bowring et al., 2003; Calver et al., 2004) glaciations, or could represent a unique episode.

Deposition of the lower part of the Kingston Peak Formation, including the glacial Surprise member, was contemporaneous with extensional tectonic activity, likely related to initial stages of continental rifting as implied by variable basement lithologies, rapid lateral thickness changes, and the identification of buried syndepositional faults (Miller, 1985; Prave, 1999). A second extensional event may have occurred during deposition of the upper part of the Kingston Peak Formation, again suggested by abrupt lateral facies changes, buried normal faults, and incised valleys (Prave, 1999). Unlike the older extensional event, which was likely an aborted rift in the Great Basin region, the younger episode has been interpreted by some to reflect the break-up unconformity, located at the base of the Noonday Dolomite, associated with true continental rifting (Prave, 1999).

The Johnnie Formation, the focus of this investigation, occurs ~400 m above the contact between Kingston Peak Formation and the Noonday Dolomite, and thus, is commonly thought to have been deposited on a thermally subsiding passive margin, well after the rifting recorded in the Kingston Peak Formation. It contains mixed siliciclastic-carbonate lithofacies and is comprised of at least five sequences, although the sequence boundaries display vastly different erosional magnitude, discussed below (Stewart, 1970; Summa, 1993). The strata are locally continuous and interpreted to represent shallow marine deposition with some fluvial influence. Stromatolites are abundant in the carbonate units (Awramik et al., 2000; Benmore, 1978). The Rainstorm Member is the uppermost part of the Johnnie Formation and is the only regionally continuous and formally named sub-unit in the formation. A regionally extensive marker bed, the Johnnie Oolite, occurs near the base of the Rainstorm Member (Stewart, 1970), and has an estimated 16,000 km^2 outcrop extent. The post-oolite Rainstorm Member includes a succession of laminated and hummocky cross-stratified quartzite, siltstone, shale and carbonate. As many as 10 thin beds of seafloor precipitates are found within this interval (Corsetti et al., 2004; Pruss and Corsetti, 2002); the precipitate-bearing beds record a pronounced negative $\delta^{13}C$ anomaly, with an isotopic nadir of −11 per mil PDB (Corsetti and Kaufman, 2003).

A major incision surface cuts into the upper part of the Johnnie Formation removing the pink carbonates and the Johnnie Oolite at certain localities along strike (Abolins et al., 2000; Summa, 1993). Coarse incised valley fill is followed by a succession of featureless mudstone and siltstone, which is in turn truncated by the base of the overlying Stirling Quartzite. The precise age of this incision is unknown. However, deep incised valleys occur in the Wonoka Formation, Australia, well above the so-called "Marinoan" glacial deposits and the Nuccaleena cap carbonate and in association with highly negative

$\delta^{13}C$ (Calver, 2000). The geochronology of Neoproterozoic glacial deposits is currently in a state of flux, but if Calver et al. (2004) are correct, then the Marinoan glaciation took place ca. 585–580 Ma and the unusually negative $\delta^{13}C$ values in the Wonoka Formation, and via correlation, the Rainstorm Member carbonates, would postdate 585 Ma (Corsetti and Kaufman, 2003). This is in good agreement with the scheme proposed by Christie-Blick and Levy (1989), which correlates the Johnnie incision to incised-valley units in Utah that occur below the rhyolites in the Browns Hole Formation dated at 580 Ma.

3. Study area and methods

The best example of a Rainstorm Member incised valley and its fill is exposed in the southern Nopah Range (Fig. 2), where it cuts deeply into the underlying Johnnie Formation and is nearly continuously exposed, in two segments, along nearly 2 km of strike length (Summa, 1993). Incised valleys are also present in the upper part of the Johnnie Formation at other localities (e.g., Trail Canyon, Tucki Wash, and northern Resting Springs Range (Abolins, 1999)), although it is unclear if they connected by a single incision surface; we are using the spectacular Nopah Range paleovalley as a case study to investigate the processes involved in its genesis. In total, 11 stratigraphic sections were measured, originating from the Johnnie Oolite, the regional marker bed located near the base of the Rainstorm Member, and continuing through the Rainstorm Member and incised valley fill to the base of the Stirling Quartzite. Eight sections were measured in the southeastern outcrop area, referred to as the Noonday area; three additional sections were measured in the northwestern outcrop area, referred to as the Gunsight area. The measured sections allowed direct comparison of depth of valley incision, thickness of valley fill, and clast size and composition of the valley fill along strike. Important contacts, such as the top of the Johnnie Oolite, base of the incised valley fill, and the base of the Stirling Quartzite, were mapped in detail to constrain the presence of syndepositional faults and reveal the structure of the incised valley. Investigation of the clast populations in valley-fill conglomerates also helped constrain the causes of incision. Glacial transport would be strongly supported if striated and/or exotic cobbles were present in the valley fill. However, contemporaneous glaciation cannot be rejected solely by the absence of striated or exotic clasts as it is possible that ice sheets formed on continents other than Laurentia. Alternatively, if rift-related uplift or reactivated extensional tectonism drove incision the majority of clasts would be derived from the local area and, in the case of active rifting, exotic clasts would largely be excluded by thermal doming of the rift shoulder.

4. Rainstorm Member incised valley

4.1. Fabric, matrix, and clast composition

The incised valley fill is a massive breccia or conglomerate nearly exclusively composed of brown limestone clasts (Fig. 3A), ranging in size from cm-scale subangular pebbles to large boulders. In addition, two outsized blocks, exceeding 10 m in maximum dimension, occur in the Gunsight area. One of these is a 15 m diameter block of orange-brown lime mudstone located at the base of the coarse valley fill in the southeastern Gunsight area; the other is a raft of bedded brown stromatolitic limestone 3 m × 10 m in size located in the upper part of coarse valley fill in the northwestern Gunsight area. The valley fill breccia is largely disorganized and poorly to moderately sorted, with some localities containing cobble- and boulder-sized clasts and others dominated by pebble- and small cobble-sized clasts. No sedimentary structures were observed in the breccia unit and there is little visible grading of clast size from base to top. Clast size instead varies laterally over distances of a few hundred meters within the breccia bed. The fabric is usually clast-supported, especially in locations with larger clast sizes, but can be matrix-supported but still clast-rich where smaller clasts predominate. The matrix varies from gray, coarse to very coarse quartz sand, typical in the Noonday area, to dark brown, medium to fine sand, more typical of the Gunsight area. Cobbles of lime mudstone are the most abundant clast type, although a small proportion of clasts contain columnar stromatolites (Fig. 3B). Green and brown siltstone pebbles and cobbles, including at least one thinly bedded clast that underwent plastic deformation (Fig. 3C), were also observed in the incised valley fill. The similarity between brown-weathering lime mudstone and the columnar stromatolites, as well as the siltstone lithotypes, in the valley fill to underlying units in the Johnnie Formation implies a local derivation for nearly all of the clasts. Three rounded quartzite cobbles were also present in the incised valley fill (Fig. 3D). These white, recrystallized quartzites are similar to units from the Crystal Spring Formation, the oldest sedimentary unit in the region located ∼2.5 km beneath the Rainstorm Member; however, they may have been recycled via underlying Kingston Peak Formation diamictites or sourced from Crystal Spring rocks previously uplifted during either of the two Kingston Peak rifting events. A small proportion of clasts (<1%) is

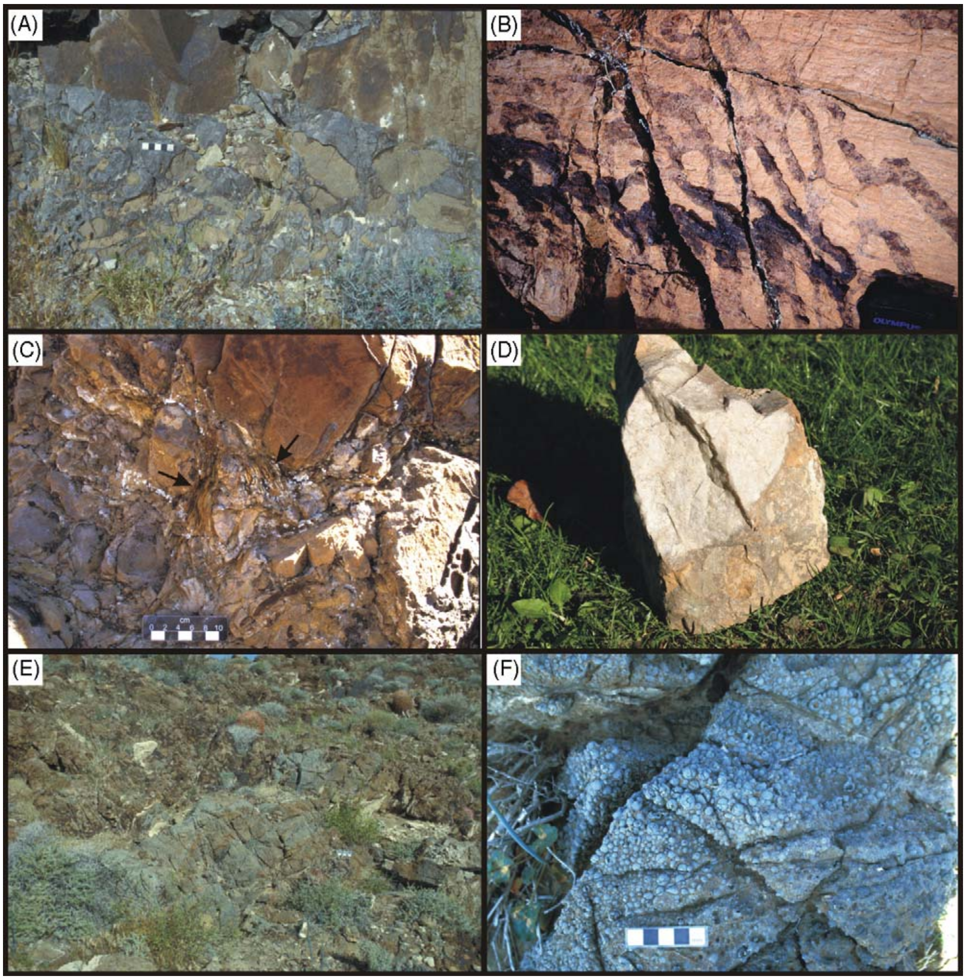

Fig. 3. Representative examples of clasts from incised valley fill breccia. (A) Abundant brown lime mudstone clasts. (B) Brown stromatolitic limestone clast. (C) Folded thinly-bedded siltstone clast, indicated by arrows. (D) White quartzite clast in hand sample. (E) Large block of gray Beck Spring Dolomite. (F) Detail showing large ooids from Beck Spring Dolomite clast.

represented by blue-gray oolitic limestone, including one 2 m long block (Fig. 3E). The 1–10 mm diameter "giant ooids" present in these clasts (Fig. 3F) are unique and diagnostic of oolitic units from the Beck Spring Dolomite (Corsetti and Kaufman, 2003), an older Neoproterozoic unit located more than 2 km stratigraphically below the Johnnie Oolite (Fig. 1).

4.2. *Incised valley fill stratigraphy*

The 11 measured stratigraphic sections document significant downcutting and rapid thickness changes of the coarse incised valley fill (Fig. 4). In most sections, the valley incises to a depth of 40–80 m above the Johnnie Oolite, although at its deepest point the valley is inferred to cut down to below the oolite bed itself (sections 2 and 3). Everywhere it is exposed, the Johnnie Oolite is overlain by 4–5 m of purple mudstone and 25–35 m of brown to gray lime mudstone and calcareous sandstone (sections 1, 4–8, 10–11). Rainstorm Member sediments immediately underlying the incised valley vary in thickness due to erosion by coarse valley fill deposits, and are composed predominantly of purple or green mudstone. Gray quartzite beds occur within the siltstone unit below the incised valley in sections 4–6. The incised valley breccia itself does not display any bedding and ranges from 90 cm to 15 m in thickness where present, and pinches out to the northwest of section 1 (Gunsight area) and in sections 10 and 11 in the southeast Noonday area. Coarse valley fill deposits are overlain by a structureless brown to green siltstone unit varying in thickness from 12 to 130 m, which itself is truncated by the base of the Stirling Quartzite. Reconstruction of the incised valley cross-profile indicates a depth of 50 m in

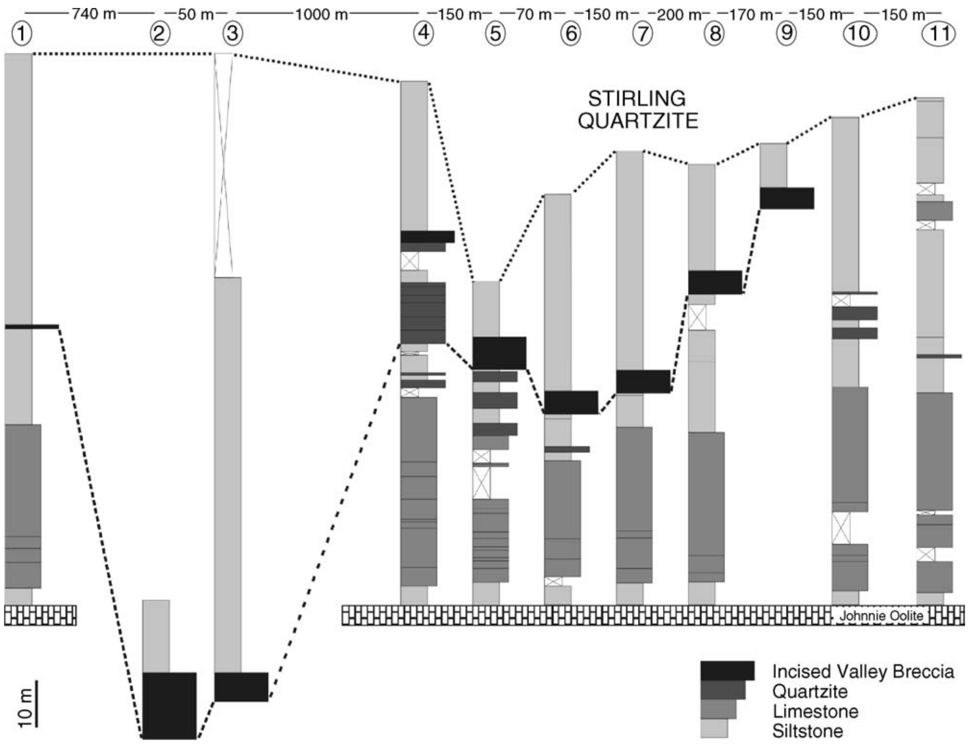

Fig. 4. Measured sections showing pattern of valley incision. Maximum depth of incision is ∼120 m. Horizontal distance not to scale; distance between sections is noted above section numbers.

the Noonday area, and an approximate depth of 120 m for the entire structure (Fig. 4). The valley is approximately 2500 m wide. Incision is gradual in the Noonday area but displays abrupt downcutting and significant thickness changes in the Gunsight area.

4.3. Depositional mechanisms

The disorganized, poorly- to moderately-sorted, clast-supported fabric of the incised valley breccia suggests that it was deposited by sediment-gravity flows, likely sourced predominantly from nearby walls of the incised valley as shown by the nearly monomictic nature of the clast populations and the noticeable fining of clast sizes toward the center of the valley. The unit may have simply been generated by collapse and shedding of blocks from the valley walls; however, rare projecting clasts (e.g., Fig. 6C) and clasts of lithotypes other than the brown lime mudstone typical of the underlying Johnnie Formation (e.g., Beck Springs Dolomite and Crystal Spring Formation) support a debris flow origin for at least some of the beds. The texture of the valley fill breccia is broadly consistent with deposition either in subaerial alluvial fans or as submarine debris flows. Large blocks present in the incised valley fill are interpreted as olistoliths within the debris flow units, either sourced directly from valley walls or transported down the valley axis.

5. Detailed mapping and evidence for syndepositional faulting

There are three lines of evidence supporting synsedimentary faulting as the primary cause of incised valley formation: abrupt incision, the presence of buried normal faults near points of significant incision, and lateral trends in clast size relative to inferred fault scarps. Abrupt incision and rapid thickness changes displayed by the coarse valley fill, especially in the Gunsight area, are suggestive of fault control. In contrast, the valley profile is more gradual and smooth in the Noonday area. However, further detailed mapping in the Noonday area revealed widespread small-displacement normal faulting affecting the Johnnie Oolite (Fig. 5B). Although some of these faults also offset lower beds of coarse valley fill, upper beds of incised valley breccia are continuous across the faults (Fig. 5D), implying that fault movement was contemporaneous with early stages of incised valley development. However, small-displacement faults, such as these, were extremely common during Tertiary Basin and

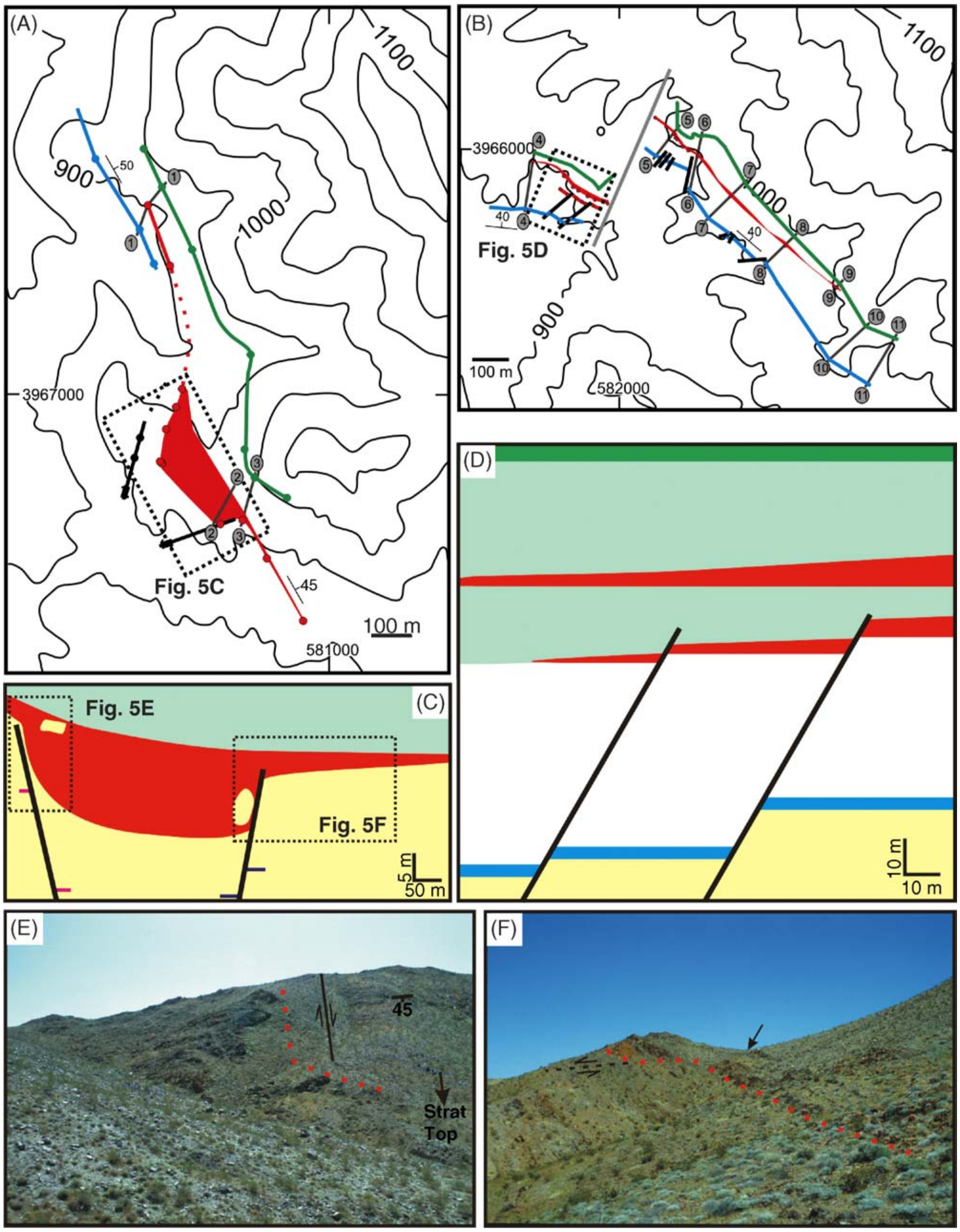

Fig. 5. Mapped contacts of Johnnie oolite (blue), incised valley breccia (red), and base of Stirling Quartzite (green). (A) Gunsight area. (B) Noonday area. (C) Schematic cartoon cross-section of valley incision, synsedimentary faults, and large olistolith blocks in Gunsight area. (D) Cartoon cross-section showing synsedimentary faulting and incised valley fill in northwest Noonday area. (E) Field photograph illustrating sharp downcutting of incised valley breccia (massive dark unit to the left of dotted line) over buried normal fault at the northwest margin of the Gunsight valley. Note the outcrop of bedded Johnnie Formation to the left of the strike and dip symbol. (F) Field photograph showing orange-brown limestone olistolith and sharp downcutting over buried normal fault at the southeast margin of the Gunsight valley. The approximate trace of the fault is not visible but is indicated by the dotted line. Note that the prominent dark layer (arrow), which represents another breccia unit above the basal incised valley fill, is continuous across the field of view, providing direct evidence that the underlying normal fault ceased movement before the deposition of the second breccia unit.

Range extension, suggesting that they may in fact not be Neoproterozoic structures (Prave, personal communication). The most convincing evidence for a tectonic influence is found in the Gunsight area, where abrupt incision is also spatially correlated to the position of buried normal faults (Fig. 5C). A normal fault with approximately 5 m of displacement forms the sharp southeastern margin of the incised valley (Fig. 5F), whereas the northwestern wall is located near a more significant fault with 18 m of normal displacement (Fig. 5E). Although these faults are closely linked with abrupt downcutting within the valley, they did not have enough displacement to create the 120 m deep valley itself; potential valley-bounding structures were not identified within the study area. However, it is possible that more significant normal faults are present in the area southeast of section 1, where the major downcutting of the incised valley breccia is localized and where outcrop is covered by large talus blocks of Stirling Quartzite shed from cliffs above (Fig. 5A). No synsedimentary faulting of the Johnnie Oolite is observed in the northwest and southeast regions where incised valley deposits thin and pinch out.

Thickness and the average clast size of the coarse incised valley deposits are also broadly controlled by the presence of buried normal faults. Large blocks are present in the incised valley fill near the northwest and southeast fault-controlled margins in the Gunsight area (Fig. 6A and B), implying they were olistoliths likely shed from nearby fault scarps. A 3 m × 10 m block of brown stromatolitic limestone is present in upper parts of the coarse incised valley fill at the northwest edge of the Gunsight valley (Fig. 6B), and a 15 m diameter block of orange-brown limestone occurs immediately adjacent to the normal fault that controls the southeast margin (Fig. 6A). In addition to these large olistoliths, the average clast size decreases with increasing distance from the buried faults. In the Noonday area, the thickness of the breccia decreases from 3 m in the central region to approximately 1 m in the northwest. Large boulders (50–150 cm in size) are common in the central region along with predominantly large cobble-sized clasts (Fig. 6C), whereas only pebbles and small cobbles are present in the thinner beds in the northwest and southeast regions (Fig. 6D).

6. Evidence for glaciation?

Neoproterozoic glacial deposits, such as the diamictites of the underlying Kingston Peak Formation, contain abundant evidence for contemporaneous glaciation, including extrabasinal "exotic" clasts, striated clasts, and dropstones. The coarse incised valley breccias of the Rainstorm Member, in contrast, contain none of these glacial signals. Nearly all clasts are locally derived from lower units in the Johnnie Formation, with a minority from older Neoproterozoic units in the basin. No striated clasts are observed, although the predominantly limestone lithology of the clasts would be unlikely to retain striations. The few quartzite clasts observed here, which are the most likely to preserve striations in this succession as demonstrated in the underlying Kingston Peak Formation (Miller, 1982), were not striated. No drop-

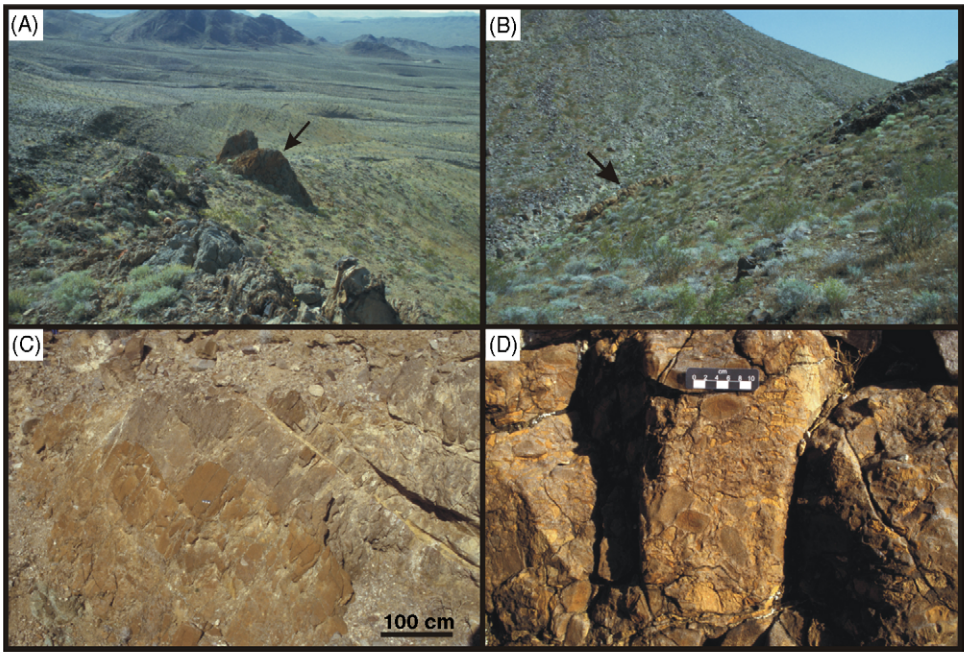

Fig. 6. Sedimentary features of incised valley fill breccia. (A) 15 m diameter block of brown limestone at base of incised valley fill, southeast margin of Gunsight valley (arrowed). (B) 3 m × 10 m limestone block (arrow) in incised valley, northwest margin of Gunsight valley. (C) Coarse incised valley fill breccia. (D) Fine incised valley fill breccia, composed mainly of pebble- and cobble-sized detritus.

stones are present, either in the underlying Rainstorm Member or in the 12–130 m of siltstone forming the upper unit of the incised valley fill. Although the absence of local glacial indicators cannot conclusively rule out glacio-eustatic drawdown due to continental ice sheets in other regions or on other continents, the close correlation between incision, breccia thickness, and clast size with synsedimentary normal faults strongly supports a primary tectonic control on valley location and formation.

7. Tectonic implications

Two major extensional events have previously been identified in the southern Cordillera, represented in the Kingston Peak Formation (Miller, 1985; Prave, 1999) and likely correlative (although possibly diachronous) to the two primary rift episodes in the northern Cordillera (Colpron et al., 2002). According to previous interpretations, the passive continental margin in the southern Cordillera was initiated during deposition of the Noonday Dolomite (Prave, 1999; Stewart, 1970). However, the identification here of ∼120 m deep, structurally controlled incised valleys in the Rainstorm Member of the Johnnie Formation implies that the tectonic history of the southern Cordillera was more protracted (e.g., Fedo and Cooper, 2001). Similar incised valleys are located at comparable stratigraphic positions in Utah and Idaho (Christie-Blick and Levy, 1989), potentially signifying a major regional extensional event if they are contemporaneous.

The Rainstorm Member incised valleys, along with other Ediacaran-age incised valley in the southern Cordillera, may reflect a third continental rifting event with the implication that at least three continental blocks or fragments separated from western Laurentia during the Neoproterozoic. The presence of clasts derived from the Pahrump Group (e.g., quartzite clasts from the Crystal Spring Formation), which lies as much as 2.5 km stratigraphically below the Rainstorm Member, may lend support to an extensional model, possibly in conjunction with mantle plume doming to produce the necessary km-scale uplift (e.g., Williams and Gostin, 2000). The presence of volcanic units, such as the Browns Hole Volcanics in Utah, stratigraphically above incised valleys (e.g., Christie-Blick and Levy, 1989) may also be consistent with a mantle plume hypothesis. However, the presence of exotic clasts alone does not require 2.5 km of uplift during formation of the Rainstorm Member incised valleys, as the older units may instead have been uplifted during either or both of the extensional events that occurred during deposition of the Kingston Peak Formation and may, therefore, have been exposed upslope during deposition of the incised valley breccia.

In addition, significant tectonic adjustment can occur in a passive margin setting, as intraplate stresses can cause either extensional or contractional reactivation during the thermal subsidence phase, long after continental separation (Cloetingh and Kooi, 1992; Fedo and Cooper, 2001; Ziegler and Cloetingh, 2004). For example, the Atlantic passive margin displayed significant tectonism, synsedimentary faulting, and anomalous rapid subsidence during the Cenozoic (Alves et al., 2003; Bartholomew et al., 2002; Cloetingh and Kooi, 1992). Similarly, the Paleozoic continental margin in the northern Cordillera also underwent several significant events of renewed extensional tectonism without continental rifting throughout the early Paleozoic, producing synsedimentary normal faulting, rapid lateral facies changes, and coarse fault scarp-sourced breccia units (Pyle and Barnes, 2003). It is, therefore, most likely that the Rainstorm Member incised valley represents similar tectonic reactivation, not continental separation, in the southern Cordillera during the latest Neoproterozoic, although the potential contribution of mantle plume-related uplift and associated faulting cannot be eliminated.

8. Conclusions

A major incised valley in the Rainstorm Member of the Johnnie Formation in the Death Valley region is 120 m deep and contains a coarse limestone breccia composed of clasts and large olistoliths derived from underlying Neoproterozoic units. Detailed mapping of the incised valley indicates that locations of significant incision, clast size, and breccia thickness are spatially correlated to synsedimentary normal faults, implying a primary tectonic control on valley location and formation. In contrast to the strong linkage to syndepositional tectonism, there is no evidence supporting contemporaneous glaciation in the region. The tectonic influences on valley formation imply that the southern Cordillera underwent a period of reactivated extensional tectonism in the latest Neoproterozoic, unrelated to continental separation and similar to the renewed extension documented in the northern Cordillera during the early Paleozoic.

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