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INSIDE

Alamo Megabreccia: Record of a Late Devonian Impact in Southern Nevada

John E. Warme, *Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401*

Charles A. Sandberg, *395 South Lee Street, Lakewood, CO 80226-2749*

ABSTRACT

The Alamo breccia is probably the most voluminous known outcropping carbonate megabreccia. It occupies ~4000 km^2 across 11 mountain ranges in southern Nevada, has an average thickness of ~70 m, and contains a volume of 250+ km^3. The breccia is a single bed, of early Frasnian (early Late Devonian) age, that formed in the wake of a giant slide that deposited a lower chaotic debrite, containing clasts as large as 80 × 500 m, and an upper exquisitely graded turbidite. It is anomalously intercalated with cyclic shallow-water platform carbonates of the Guilmette Formation. The Alamo breccia is interpreted as a product of the Alamo event, a nearby marine impact of an extraterrestrial object, whereby impact-generated crustal shock waves and/or marine superwaves detached the upper ~60 m of platform along a horizontal surface. Loosened bedrock slid seaward across the platform, and some of it accumulated as the lower debrite. Rock-water exchange induced landward-propagated tsunami(s), whose uprush and/or backwash deposited the upper turbidite, partly above sea level. Evidence for impact includes shocked-quartz grains, an iridium anomaly, and reworked conodonts, all found only within the breccia. Because the Alamo breccia is not known outside of Nevada, and because the early Frasnian time of the Alamo event is not noted for accelerated extinctions, being ~3 m.y. before the Frasnian-Famennian impact(s) and biotic crisis, the impact was probably only of moderate size.

INTRODUCTION

The Alamo breccia, a newly recognized carbonate megabreccia, is an anomalous event–stratigraphic bed of immense proportions, probably the largest megabreccia known in surface exposures. It was emplaced in a geologic instant of

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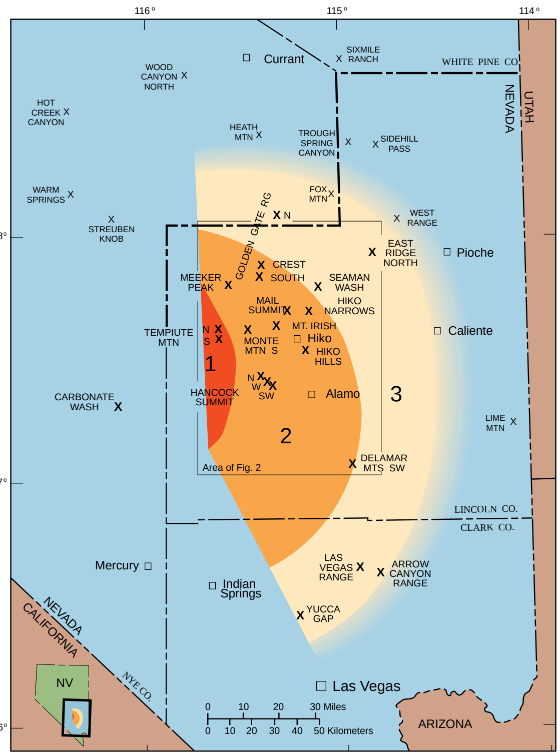

Figure l. Study area showing towns (squares), Devonian localities (x's), and lateral distribution zones of Alamo breccia. Breccia thicknesses: zone 1, ~130 m; zone 2, ~60 m; zone 3, <1–10 m.

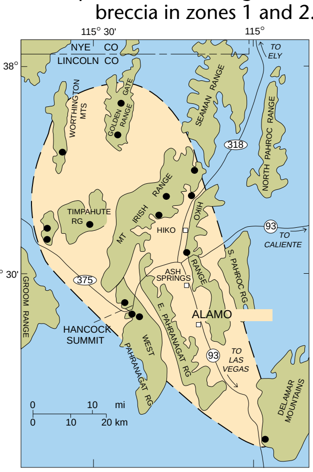

Figure 2. Enlargement of inset in Figure 1 showing mountain ranges, outcrop localities, and the perimeter enclosing Alamo breccia in zones 1 and 2.

Figure 3. View northward from the Hancock Summit area (see Fig. 2) of West Pahranagat Range, showing the 55-m-thick Alamo breccia (AB) within the 600-m-thick Guilmette Formation. The Guilmette begins at the yellow slope-forming interval (YSF in Fig. 4) in the saddle ~150 m below the breccia, is underlain by the Simonson Dolostone at left, and is overlain by the West Range Limestone and/or Pilot Shale on dip slope at right.

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early Late Devonian time and is now preserved within the Guilmette Formation of southern Nevada. The breccia, as yet informally named, crops out in 11 mountain ranges around the community of Alamo, Nevada (Figs. 1–3). It spans a minimum area of 4000 km^2, has an average thickness of ~70 m, and represents detachment, mobilization, and resedimentation of at least 250 km^3 of Devonian carbonate rock.

The Alamo breccia represents an extraordinary style of carbonate-platform collapse and submarine slide, now preserved as a single bed with the characteristics of a debrite (debris-flow deposit) in the lower part that evolved into a capping turbidite (Figs. 4, 5). It is anomalously intercalated within cyclical shallow-water carbonate-platform facies of the Guilmette Formation (Figs. 3–6), rather than occurring in deeper water as expected. Its huge magnitude, singular epiplatform occurrence, horizontal delamination from platform bedrock, and exotic components including shocked quartz, iridium, and reworked conodonts, all indicate genesis from the consequences of an impact of an extraterrestrial object with Earth, named the Alamo event (Warme et al., 1991; Warme, 1994).

Discovery of the Alamo breccia coincides with current intense interest in geologically short-lived but significant events (e.g., Clifton, 1988) and new appreciation for the possible physical and biological effects of extraterrestrial impacts (e.g., McLaren and Goodfellow, 1990; Sharpton and Ward, 1990). This preliminary report describes the breccia, discusses its genesis as a catastrophic bed, and presents evidence that it was triggered and magnified by a nearby marine impact of moderate size.

SUBMARINE SLIDES, CARBONATE MEGABRECCIAS, AND TSUNAMITES

Many enormous submarine debrites and/or turbidites, comparable in extent and volume to the Alamo breccia, are known from both modern (e.g., Piper et al., 1988; Moore et al., 1994) and ancient (e.g., Macdonald et al., 1993) settings. Catastrophic failure of the seaward margins of present and past carbonate platforms results in voluminous carbonate megabreccias that commonly contain huge transported blocks (e.g., Cook and Mullins, 1983; Hine et al., 1992). However, all large-scale marine mass-flow deposits described to date, whether terrigenous or carbonate, intercalate with thinner resedimented beds and were interpreted to accumulate in relatively deep water seaward from shelf or platform edges.

Massive shelf-edge slumping causes a water-for-rock volume exchange that induces an onshore tsunami. Numerous massive Quaternary underwater slumps occurred adjacent to the Hawaiian Islands, and each potentially triggered destructive onshore waves (Moore et al., 1994). One example is suspected of causing a prehistoric catastrophic tsunami that formed an uprush 375 m above sea level on Lanai, Hawaii, leaving a deposit (tsunamite) of coral and other rubble in its wake (Moore and Moore, 1988). However, tsunamis produced by underwater landslides would likely be dwarfed compared with those from oceanic extraterrestrial splashdowns; the waves could be as high as the target water depth, conceivably 1000 m or more (Silver, l982), but few deposits from such waves have been identified. Probable impact-related slump deposits and tsunamites were described at the Cretaceous-Tertiary (K-T) boundary in cores from the Gulf of Mexico as well as in circum-gulf outcrops (e.g., Smit et al., 1994). An

Megabreccia *continued on p. 3*

Megabreccia *continued from p. 2*

Eocene breccia in the subsurface under Chesapeake Bay was first regarded as the tsunamite from a North Atlantic impact, then was reinterpreted as brecciated target rock (impactite) within the actual crater (Poag and Aubry, 1995). Owing to the numerous exposures and well-understood stratigraphic framework of the Alamo breccia, it provides a useful comparison and basis for interpreting other less accessible catastrophic deposits.

GEOLOGIC SETTING OF THE ALAMO BRECCIA

Southern Nevada falls within the Basin and Range physiographic province, where Paleozoic rocks are exposed along linear mountain ranges, buried deeply in intervening valleys (Fig. 2), deformed by post-Devonian orogenies, and covered by Cenozoic volcanic rocks. The area of the Alamo breccia in Figures 1 and 2 is not palinspastically restored.

Stratigraphic Framework

From Cambrian into Late Devonian time, a westward-facing linear carbonate platform rimmed the west side of the North American craton, trending approximately north-south through central Nevada (e.g., Poole et al., 1992). The Alamo breccia is within the shallow-platform facies of the Guilmette Formation, except in its westernmost known exposure at Tempiute Mountain (Figs. 1, 2) where it is overlain by ~300 m of deeper water facies of the correlative Devils Gate Limestone (Fig. 4). The Guilmette comprises ~150 shallowing-upward carbonate-platform cycles (Fig. 3) averaging ~5 m thick. The Alamo event slide consumed a stratigraphic interval ~60 m thick and containing ~10 to 15 cycles. Cycle tops directly beneath the breccia exhibit dolomitized algal laminites, desiccation cracks, and fenestral fabrics that indicate upper-intertidal to supratidal carbonate platform environments. Lithofacies directly above the breccia are more variable and demonstrate a post–Alamo event westward-dipping ramp.

Conodont Biofacies

Analyses of 75 conodont samples from the lower part of the Guilmette Formation in the study area yielded both paleoenvironmental information, crucial for understanding the Alamo breccia, and an exact biostratigraphic date for the bed. Conodont samples include 30 from the Alamo breccia and 45 from the Guilmette confining beds. The paleoecological interpretation of the lower Guilmette, including the interval of the Alamo breccia (Sandberg and Warme, 1993; Warme and Sandberg, 1995), employs the conodont biofacies scheme described by Ziegler and Sandberg (1990). As shown in Figures 4 and 5, platform cycles below the breccia contain shallow-subtidal biofacies and indicate water depths of 10 m or less. Collections from fossiliferous postbreccia beds at or above its top indicate landward shallowing, from 60–100 m on the west to 10–20 m toward the east. Samples from easternmost localities (zone 3 in Fig. 1) were largely barren of conodonts. Samples collected within the lower part of the breccia, from both platform-derived clasts and breccia matrix, yielded shallow-water biofacies, as expected. However, samples from the upper part contain admixed deep-water contemporary Devonian and reworked Ordovician species, probably derived from deeper environments far to the west.

Age and Timing of Alamo Event

Conodont age determinations show that the Alamo event is narrowly bracketed within the middle part of the *punctata* conodont Zone of Ziegler and Sandberg (1990), as shown in Figures 4 and 5, which represents ~0.5 m.y. of early Late Devonian (Frasnian) time. The *punctata* Zone was ~3 m.y. before the much-studied late Frasnian mass extinction (Sandberg et al., 1988), and has a biochronologic date of ~13 m.y. before the end of Devonian time. Because the Devonian-Carboniferous boundary has been variously dated as 340 to 360 Ma, the Alamo event was between ~355 and 370 Ma.

DESCRIPTION OF ALAMO BRECCIA

The Alamo breccia is a single bed deposited during one event. Although its internal structure varies significantly both laterally and vertically, the most obvious trends are decreasing thickness landward (eastward) and decreasing clast and matrix sizes (normal grading) upward. For descriptive purposes, the breccia is divided into lateral zones 1 to 3, from west to east (Figs. 1 and 2), and vertical units A to D, from top to base (Fig. 5).

Distribution and Lithology

To date, the Alamo breccia is known at 23 localities spread across ~4000 km^2 (Figs. 1 and 2). Thickness varies from 130 m in zone 1 to <1 m in parts of zone 3. If 70 m is taken as the average thickness, then the minimum volume of rock displaced during the Alamo event is ~280 km^3. The total distribution and volume may be much greater; they are not fully documented because of sparse outcrops and restricted access to the south and west.

The Alamo breccia is almost exclusively carbonate rock (Figs. 7–10). Its composition is limestone, except for minor synsedimentary supratidal dolostones and local but significant selective or complete dolomitization. Most clasts are recognizable components of the Devonian carbonate platform that disintegrated during the Alamo event. Quartz grains and other noncarbonate components recovered from conodont-sample insoluble residues represent «1% of the breccia volume.

Clasts and Matrix

The Alamo breccia contains a population of megascopic clasts ranging in size from sand to blocks 80 × 500 m. Breccia "matrix" is a relative term; matrix between clasts of given sizes is simply smaller fragments, regardless of their absolute scale (Fig. 8). Gravel-, sand-, and smaller sized particles are ubiquitous between blocks, but become better sorted and occupy progressively greater proportions of the volume upward, culminating in the well-graded top.

Lateral Variations: Zones 1 to 3

The Alamo breccia exhibits characteristic thicknesses, internal structures, and internal variability in each of the three zones shown in Figures 1, 2, 4 and 6.

Zone 1: Foreslope or Basin Floor. Zone 1, along the west end of Tempiute Mountain (Figs. 1 and 2), probably extends much farther westward. It is 130 m thick and is composed of a thick (~100 m) turbidite (unit A, described below) overlying a thinner debrite (unit B): the turbidite is generally finer grained than in zone 2 to the east. Maximum-sized clasts are <5 × 15 m in two dimensions. Zone 1 is interpreted as an area of platform foreslope or basin floor.

At Tempiute Mountain, twisted and fractured bedrock underlies the breccia, laced by an array of sedimentary dikes and sills injected with carbonate breccia and rich in quartz sand grains. The overlying Alamo breccia, in contrast, is relatively undeformed and weathers as a shear cliff ~100 m high. The deformation is interpreted as listric faults that moved and rotated during the Alamo event (Fig. 6; see Winterer et al., 1991). Dilated fault planes are filled with debris derived from fissure walls, overlying slope deposits, and the bypassing breccia. Margins of the fissures show liquefaction phenomena similar to that of unit D, described below, at the base of the Alamo breccia.

Zone 2: Seaward Platform. Across the broad area of zone 2, the Alamo breccia averages ~60 m in thickness, contains discontinuous giant clasts as much as 80 × 500 m, and commonly exhibits all four vertical units A to D described below.

Zone 3: Landward Platform. The Alamo breccia in zone 3 (<1 to ~10 m thick) may exhibit only a graded turbidite (unit A), with <1-m-diameter clasts, or

Megabreccia *continued on p. 4*

Megabreccia *continued from p. 3*

may be dominantly a debrite (unit B) transitionally overlain by a thin turbidite, suggesting extensive turbidity-current bypass. The debrite contains tabular clasts up to 30 m long, oriented (sub)parallel to bedding. Zone 3 breccia was stranded above sea level and subaerially exposed for a significant time before deposition of the next platform cycle. It may be selectively eroded at the top, bleached by dolomitization, or karsted, in contrast to its confining beds.

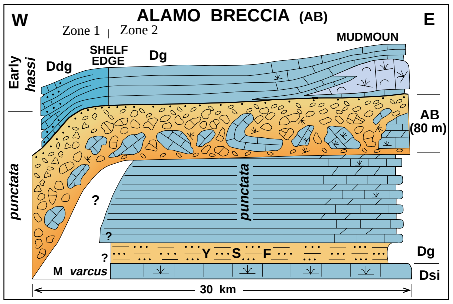

Figure 4. Diagrammatic cross section of Alamo breccia (AB) within the zone 2 shallow-water Guilmette Formation (Dg) and equivalent zone 1 deep-water Devils Gate Limestone (Ddg). The Upper Simonson Dolostone (Dsi) is within the Middle Devonian Middle *varcus* conodont Subzone, overlain by the basal Guilmette yellow slope-forming interval (YSF). Overlying cyclical carbonate rocks and the Alamo breccia are within the early Frasnian *punctata* Zone. Beds beginning 4–10 m above the breccia are in the Early *hassi* Zone.

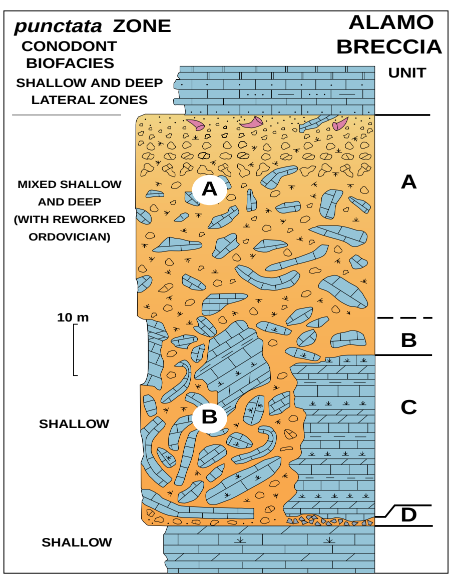

Figure 5. Vertical units A to D, and conodont biofacies paleobathymetry. Units D and C, if present, are together: D is a zone of bedrock fluidization; C is giant clasts preserved in the process of tearing loose and incorporating into the slide. Unit B is chaotic debrite, beginning at the base of the breccia where unit C blocks were removed. Unit A, transitional upward from unit B, is a well-graded turbidite capping breccia everywhere. Tufted symbols represent stromatoporoids; cones represent corals concentrated at the top.

Vertical Units

The Alamo breccia is composed of from one to four vertical units, A to D. They are arranged from top to base as follows (Fig. 5): unit A: upper turbidite—present in all zones (1–3); unit B; lower debrite—best developed in zone 2; unit C: basal megaclasts, actually or nearly in original positions—zone 2 only; unit D: diamictite under megaclasts—zone 2 only.

Units D and C—Detachment Interval and Megaclasts. Units C and D are genetically related, occur together but discontinuously along the base of the breccia (Fig. 5), and illustrate the mode of epiplatform slide detachment across zone 2. Unit D is an unusual, light-gray–weathering, calcareous diamictite, <1 cm to ~3 m thick, that developed ~60 m beneath the contemporary Devonian platform

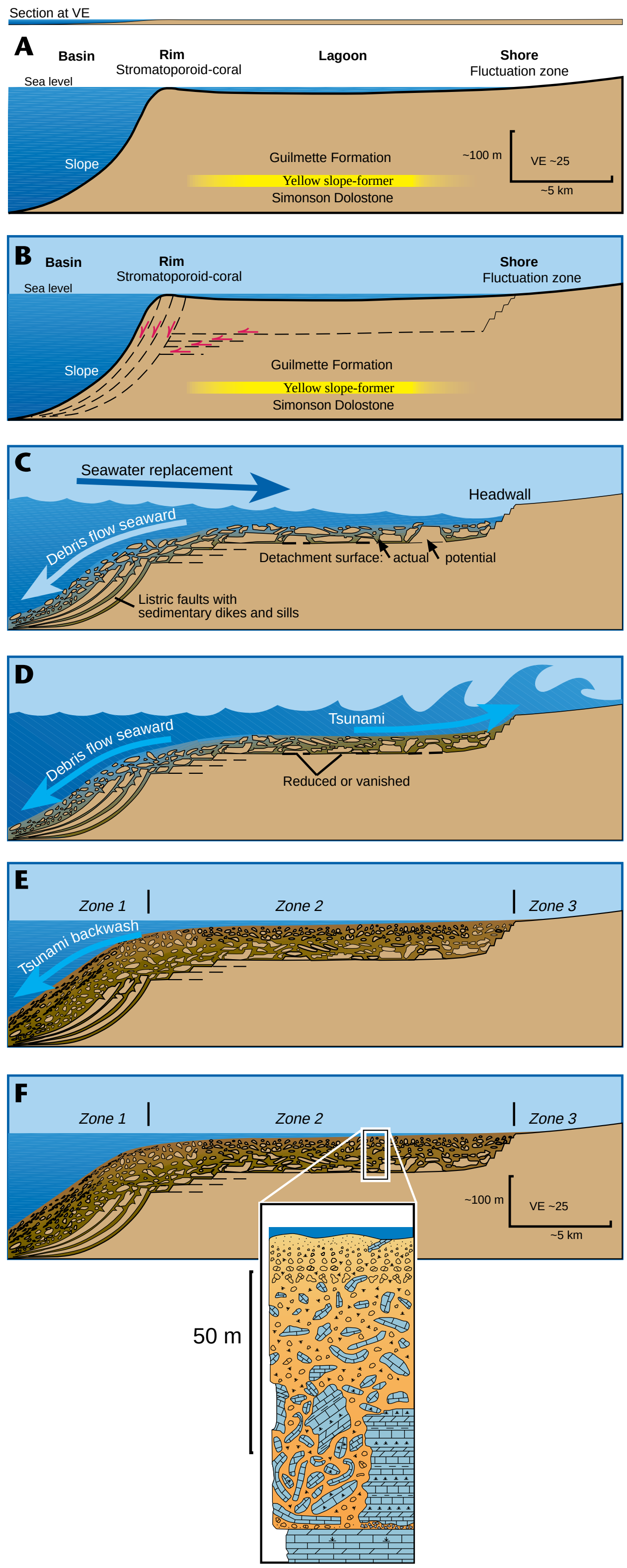

Figure 6. Interpretation of processes that produced the Alamo breccia: A: Rimmed Devonian carbonate platform at 1:1 vertical and horizontal scale. B: Platform at 25:1 vertical exaggeration. C: Platform showing two sets of fractures along which failure occurred: listric at the platform edge, and nearly horizontal across the platform. D: Platform failure: movement along listric faults created sedimentary dikes and sills, which removed lateral support from the platform. As bedrock detached and slid seaward, evacuation caused the sea surface to tilt landward. E: Tsunami caused by bedrock– sea-water exchange crossed the platform and overtopped the headward slide scar, while debris flow continued seaward. F: Tsunami backwash stranded a turbidite along the periphery of the platform (zone 3), continued across the detachment area (zone 2), and flowed into deep water beyond the platform (zone 1). G: The final product; the inset shows the giant sandwaves across the top of the breccia.

surface. The evolution of the diamictite is preserved in many localities, where within a distance of 1 m, intact bedrock changes laterally to a tight fracture-mosaic, a dilated fracture-mosaic, a melange of isolated and rotated fragments, and ultimately to the diamictite (Fig. 7). Unit D is preserved only where the huge blocks of unit C are actually or nearly in original position over it. Where unit C blocks were lifted, fragmented, and incorporated into the unit B debrite, unit D was unprotected and scoured away.

Throughout zone 2, the Alamo breccia rests at about the same stratigraphic level, where unit D cuts indiscriminately along the same or adjacent shallowing-upward carbonate-platform cycles, rarely at a bed or cycle boundary. The massive unit C blocks, directly above unit D, are (sub)parallel to bedding and have ragged, sharp lateral terminations, beyond which the debrite of unit B extends to the basal plane of the breccia (Fig. 5).

Figure 7. Characteristics of unit D fluidization, showing nearly intact bedrock (right), a mosaic of fractures (center), dilation (left-center and across base), and complete fluidization to calcareous diamictite (upper left).

Unit B—Chaotic Debrite. A bewildering spectrum of clast sizes, shapes, and orientations characterizes unit B. The largest clasts are tabular, tens to hundreds of meters in longest dimension, and fully encased in unit B matrix, in contrast to the unit C clasts along the base of the breccia. Smaller unit B clasts are tabular to equidimensional (Fig. 8), and some are intricately deformed or preserved in the process of peripheral fragmentation into finer grained matrix. At some localities, multiple slabs >100 m long rode over one another toward the top of the breccia and formed logjamlike megafabrics. Beds at the base of unit B are preserved in all stages of being ripped up, injected below by matrix, torn away, and incorporated into the breccia. Figure 9 shows a spectacular example.

Unit A—Graded Bed. Unit A is a -well-organized turbidite that transitionally overlies the chaotic fabric of unit B. It ranges from roughly graded meter-sized clasts near the middle of the breccia to an exquisitely graded 5–30 m interval (100 m in zone 1) at the top. The sorting process left zones rich in domal boulder- to cobble-sized stromatoporoids and their hydraulically equivalent lithoclasts, fragments of tabular stromatoporoids and their hydraulic equivalents, and, near the top, concentrations of fragmented corals, brachiopods, and their equivalents. The topmost 1 m commonly exhibits calcarenite cross-bed sets up to 30 cm high, representing the climbing ripples of Bouma turbidite interval C, overlain by a thin, finer grained, horizontally laminated Bouma interval D. At some localities the upper 1 m exhibits compound grading caused by repeated scour and fill during waning runoff.

The top of unit A also contains rare large clasts, as much as 10 × 30 m, that interrupt the graded profile. They suggest that the underlying debris flow still moved as a viscous mass and that clasts from below were buoyed upward and incorporated into the accumulating turbidite.

Upper Boundary

Unit A usually exhibits complete grading from boulder conglomerate upward to calcareous mudstone. In zone 1, the very fine grained top of the breccia merges with overlying deep-water limestones, and in zone 3 the karsted top is overlain by peritidal carbonate-platform beds. However, zone 2 is more variable. Pebble-sized clasts at the top may represent the broad crests of giant sediment waves, hundreds of meters apart (e. g., Bretz, 1969; Moore and Moore, 1988), perhaps stranded above sea level. They may have separated parallel linear lagoonal depressions, evidenced at other localities by bioturbation across the upper contact.

EXOTIC COMPONENTS

Three significant exotic components occur within the Alamo breccia and are not present in overlying and underlying beds.

Shocked Quartz Grains

Insoluble residues of conodont samples from the Alamo breccia concentrate unusual quartz grains (Fig. 10), common in zone 1 and progressively scarcer land-

Megabreccia *continued on p. 6*

Figure 8. Upper part of the Alamo breccia showing large clasts (beneath the person) that are transitional to the graded bed above. The small, dark clasts are mostly whole or fragmented domal stromatoporoids. West Pahranagat Range.

Figure 9. A spectacular example of beds deformed and preserved in the process of detachment and incorporation into the Alamo breccia, West Pahranagat Range. A folded package, ~20 m thick, was pried up along the base of the slide by a huge, chisel-shaped clast moving from the right. The massive bed over the fold is 30-m-thick graded units B and A. Total breccia thickness is 60 m.

Megabreccia *continued from p. 5*

ward. By optical petrography, these grains exhibit one to six sets of internal parallel lamellae and mosaic extinction, both typical of shock metamorphism associated with impacts (e.g., Stöffler and Langenhorst, 1994). By transmission electron microscopy (TEM), they reveal micrometer-scale parallel deformation structures and fractured and rotated crystal fragments between lamellae (Leroux et al., 1995). The grains display unusual peripheral studding by crystals of iron oxides and sulfides (Fig. 10), which may represent diagenetic products or even impact phenomena. The shocked grains were air- or water-borne from target rock.

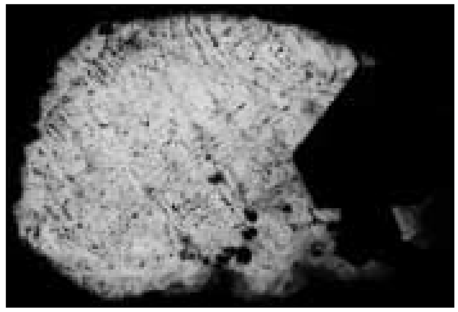

Figure 10. Thin section of a shocked-quartz grain showing four to six directions of shock lamellae, trains of inclusions along lamellae, and large displacive hematite crystals; the longest grain dimension is ~150 μm.

Iridium

Samples from within and above the Alamo breccia were analyzed for Ir and other elements that signify extraterrestrial material (Alvarez et al., 1980). Two sample profiles across the top of the breccia, ~100 m apart in the Worthington Mountains (Figs. 1 and 2), showed similar results. Background Ir in the area is <10 parts per trillion (ppT). Sixteen samples spread ±0.5 m from the breccia top showed slight Ir elevation, averaging 20.1 ppT, the maximum being 39 ppT. Eight samples from 0.5–1.5 m below the top averaged 69.4 ppT, the maximum being 139 ppT. Results are not available for samples from 1.5–12 m, but six samples from 12–55 m averaged only 8.5 ppT. The Ir may have been diagenetically mobilized a few meters downward from the breccia top. Alternatively, the Ir was water-borne to the site (see Displaced Conodonts below) and accumulated with the thick unit A graded bed, making the anomaly very significant because of the overwhelming carbonate debris that must have greatly diluted any accumulating Ir (and shocked quartz).

Displaced Conodonts

Collections from zone 1 and from pebbly zones of units B and A in zone 2 contain rare reworked Ordovician conodonts, probably derived from admixed target-rock fragments, and *punctata* Zone deep-water conodonts, which were probably preserved in the matrix. Both represent exotic elements, likely transported from the west beyond the platform margin.

DEPOSITIONAL HISTORY

Our scenario for the origin of the Alamo breccia, shown in Figure 6, is consistent with our field observations and sample data. (1) The setting for the breccia is the rimmed, flat-topped, Late Devonian carbonate platform of Nevada (Fig. 6, A and B). (2) Movement on two sets of fractures (Fig. 6C) detached the platform. Failure along the first set, representing relatively high angle listric faults, removed lateral support at the platform margin. Horizontal delamination along the second set allowed seaward transport of overlying beds across zone 2 (Fig. 6D). (3) The resulting debris flow created a westward-facing, flat-floored, epiplatform depression, equal in volume to the bedrock removed, and induced gravity-driven landward-propagated tsunami(s). By inertia the wave(s) overstepped the headward slide scar and flooded the adjacent platform of zone 3 (Fig. 6E). (4) Backwash stranded the thin breccia across zone 3, and dumped excess debris as a seaward-thickening turbidite over the debrite of zones 2 and 1 (Fig. 6F). The debrite was still moving seaward, indicated by absence of a clear debrite-turbidite contact and by the oversized clasts that were rafted upward into the accumulating turbidite. (5) Air- and/or water-borne shocked-quartz grains, Ir-bearing particles, and exotic conodonts were incorporated into the breccia matrix.

(6) As sea level equilibrated, the breccia in zone 3 was exposed (and eventually karsted), the shoreline was near the slide scar, giant sandwaves crossed the top and may have separated linear lagoons, and water depths increased across zone 2 into Zone 1 (Fig. 6F). The platform was temporarily converted from a rim to a ramp. (7) Post–Alamo event deep-water limestones accumulated in zone 1 and outer zone 2, and shallow-water cyclic deposition eventually resumed across inner zone 2 and zone 3.

The events shown in Figure 6 fail to account for the excess volume of breccia that was spread across zone 3, approximately filled the slide area of zone 2, and left a 130-m-thick deposit in zone 1. We believe that a nearby extraterrestrial impact intensified the processes diagrammed in Figure 6 and accounts for the volume observed. Superwave uprush and backwash amplified the tsunami generated by the debris-flow–sea-water exchange, enlarged the landward flood and withdrawal, and transported the sediment required to fill the space evacuated by the debris flow. Such superwaves best account for the exotic deep-water *punctata* Zone conodonts, which indicate a probable water depth of >300 m at the impact site, and the reworked Ordovician conodonts recovered from the breccia. The waves or associated currents may also have transported Ir and shocked quartz from the impact site. An impact could have generated immense runoff from water ejecta and rainfall from condensed vapor, which swept debris off large areas of the adjacent craton and flowed across all three lateral zones of the Alamo breccia.

DISCUSSION

Distinctive attributes of the Alamo breccia separate it from all other known catastrophic carbonate megabreccias. It was first recognized for its anomalous epiplatform framework. Its shocked quartz and Ir strongly suggested an impact trigger. Given an impact, seismic shock could have induced movement on the platform-margin listric faults, causing loss of lateral support, and generated horizontal epiplatform fractures, leading to platform delamination and failure. Radial shock waves, similar to those accompanying thermonuclear detonations, may have delaminated the platform at a uniform depth below the surface (unit D) and fractured overlying beds into approximately equal horizontal segments (unit C blocks). Concurrently, or alternatively, abrupt loading and unloading of superwaves over platform bedrock, and/or shear from catastrophic wave uprush and backwash, caused rapid oscillation of subsurface pore pressures and induced fluidization along unit D.

Several characteristics of the Alamo breccia suggest that the impact was relatively small, located near our study area, and created waves and/or currents that brought a significant volume of debris onto the platform. The reworked conodonts and shocked quartz grains are progressively less abundant in landward samples, and may have been water-borne. The broad Ir spike 0.5–1.5 m below the top of the breccia suggests subaqueous accumulation simultaneous with waning-phase deposition. Most significantly, the volume of the Alamo breccia appears too great to have come only from the shallow submarine slide shown in Figure 6. Zone 3 contains significant breccia volume, but it is landward of the slide; the depression across zone 2 is brim-full with breccia, but should have been initially almost empty and have temporarily accumulated deeper water sediments; the deposit in zone 1 is 130 m thick, and extends westward for an unknown distance. All these relations suggest that catastrophic waves, debris-laden

Megabreccia *continued on p. 7*

Megabreccia *continued from p. 6*

from a nearby impact, brought the exotic breccia components and required rock volume onto the platform.

A relatively small, local impact is also implied, because accelerated biotic extinctions are not documented within the *punctata* Zone. However, the Late Devonian in general and the Frasnian-Famennian (F-F) boundary specifically are times of extinction and rapid biotic turnover perhaps unequaled in the Paleozoic (e.g., Sandberg et al., 1988; McLaren and Goodfellow, 1990). The Alamo event occurred ~3 m.y. before the F-F boundary, but may represent one of several sequential events during the Devonian (McGhee, 1994) that destabilized many existing taxa and rendered them prone to extinction by the flux of subsequent impact, volcanic, eustatic, or other natural events (e.g., Hut et al., 1987).

CONCLUSIONS

The Alamo breccia is one of the largest catastrophic megabreccias known in terms of its area, thickness, volume, and clast sizes. In 1990 the breccia was recognized within a formation that had been well studied by previous researchers. It commonly forms the thickest cliff within Guilmette Formation outcrops (Fig. 3) but was unnoticed or misinterpreted as reef, storm, karst, or tectonic breccias, and its huge clasts were unwittingly measured and described as being in situ.

We interpret the Alamo breccia to be one result of a nearby extraterrestrial impact. We have yet to understand the details of its genesis—we seek the crater.

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