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THE ENIGMATIC QUACO COBBLES, UPPER TRIASSIC, CANADIAN MARITIMES: DEFORMATION BY TECTONICS OR SEISMIC SHOCK?

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Abstract—The most distinctive feature of the Upper Triassic (Carnian) Quaco Formation, coastal New Brunswick, Canada, is the pervasive occurrence of cm-scale circular to elliptical markings and indentations on the cobble surfaces. Also present on many of the cobbles are fractures that radiate from these indentations and spalled clast margins. The smooth-surfaced depressions that occur on most cobbles likely originated through pressure solution, potentially enhanced by a stage of tectonic compression during basin inversion. However, the radial fracturing of the clasts, grain fracturing within the clast fabric, and clast spalling could be explained as the result of concussion fracturing at points of clast contact during the passage of strong shock waves, such as those resulting from the Manicouagan impact. The open nature of some of the fractures and micro-faulting of the cobbles suggest that compressive tectonics enhanced previously formed fractures. At this time it is not possible to determine the origin of the fractures conclusively. Thus, the competing hypotheses of tectonics and seismic shock remain viable.

INTRODUCTION

Tanner (2006) noted a widespread zone of synsedimentary deformation in the Upper Triassic (Norian) strata of the Blomidon Formation of the Fundy basin, Canada. This zone of deformation had been described previously by Ackermann et al. (1995) as the result of solution collapse of evaporite beds. Tanner (2006), however, documented numerous features in the zone of deformation, such as thixotropic or hydroplastic behavior of sedimentary beds that indicate liquefaction, and thus proposed that the basin-wide zone of deformation in the lower Blomidon Formation resulted from seismic deformation. Further, Tanner (2006) noted the occurrence of a small number of grains that have features consistent with an impact origin, e.g., multiple sets of planar deformation features – toasted quartz grains – glassy spherules, and suggested that they might have originated from the Manicouagan impact, which is approximately the same age as the basal Blomidon Formation. Tanner (2006) therefore hypothesized that the seismic shock of the impact caused a sudden release of stress on the border fault for the Minas Fault zone, triggering a substantial seismic event recorded by the Blomidon strata.

The seismic effects of other bolide impacts, most notably the Chicxulub impact, have been cited previously as the cause of mass wasting processes at great distances from the impact site (Norris et al., 2000; Busby et al., 2002). The ~100 km-wide Manicouagan structure in northeastern Canada is one of the largest well-documented impact sites (Grieve, 1998). Once considered a candidate for the cause of end-of-Triassic extinctions, U-Pb zircon dating of the impact melt establishes the age of the impact as early Norian; the date of 214 ± 1 Ma by Hodych and Dunning (1992) has since been refined to 215.5 Ma by Ramezani et al. (2005). These dates accord well with the K-Ar date of 214 ± 2 Ma obtained from an impact ejecta layer in Britain (Walkden et al., 2002).

Also present in the Fundy Basin are ornamented cobbles, found in the Quaco Formation of Late Triassic age. These are similar to those described by Ernstson et al. (2001) and Bilodeau (2002) and interpreted as the result of clast collisions triggered by impact-generated shockwaves. These data caused Tanner (2003) to raise the intriguing possibility that the seismic effects of the Manicouagan impact were sufficiently powerful at a distance of hundreds of kilometers to leave a record of deformation in both the Quaco and Blomidon formations of the Fundy Basin.

QUACO FORMATION COBBLES

The Quaco Formation is part of a sequence of coarse continental clastic sediments (sandstones and conglomerates) that filled the half-graben of the Fundy sub-basin, a structural subdivision of the Fundy rift basin during the Middle to Late Triassic (Nadon and Middleton, 1985). The Quaco Formation is exposed as coastal cliffs at Quaco Head, near St. Martins, New Brunswick (Figs. 1-2). The strata comprise 215 meters of quartzite-cobble conglomerates and interbedded coarse-grained sandstones (Wade et al., 1996). Klein (1963) interpreted these facies as the deposit of an alluvial fan prograding from the basin margin, but Nadon and Middleton (1985) instead interpreted the same facies as the record of an axial braided-stream system. The age is constrained as Carnian or older by the palynology of the overlying Echo Cove Formation (Nadon and Middleton, 1985). Thus, deposition of the Quaco Formation well predates the Manicouagan impact, as described above.

The most distinctive feature of the formation is the near-pervasive presence of circular to elliptical blemishes and indentations on the otherwise smooth surfaces of cobbles in clast-supported beds (Fig. 3A). These markings, similar to those reported in other Triassic formations by Ernstson et al. (2001) and Bilodeau (2002), are present on all clast lithologies, which comprise mainly quartzite but also include volcanics and intrusives. Virtually all in-situ clasts that are visibly in point contact with surrounding clasts contain these markings, but they are absent from clasts supported entirely by sandstone matrix. The markings are nearly circular to elliptical in outline and 2 mm to 25 mm wide. Most markings host an indentation up to 5 mm deep, although many blemishes display no measurable depression of the clast surface. The surface texture of the indentations varies from smooth to rough or hackly (Fig. 3B), in some instances displaying en-echelon ridges. On the quartzite clasts, the blemishes and indentations are nearly white, contrasting with the reddish-brown hematitic coating on most clasts, and commonly surrounded by a 2 to 10 mm wide aureole that comprises a zone of closely-spaced (sub-millimeter), finely macroscopic to microscopic fractures.

Many clasts display larger fractures that extend radially up to 10 cm from the surficial circular indentations (Fig 4A-C); these typically form a concave plane at an acute angle to the cobble surface. Some of the fractures are sites of vertical and/or lateral displacement of the cobble surface; some fractures demonstrate lateral separation resulting in an opening of 1 to 2 mm at the cobble surface where a portion of the clast has partially spalled away from the clast body (Fig. 4D). Vertical (relative to the cobble surface) displacement also occurs on some fractures, in some instances with a steep reverse-fault sense of displacement (Fig. 4D). Subparallel sets of microfractures extend up 300 µm below the cobble surface and crosscut multiple grains (Fig. 5A). Millimeter-scale microstylolites are also present in most clasts. In some instances, they occur in the vicinity of the indentations, oriented approximately parallel

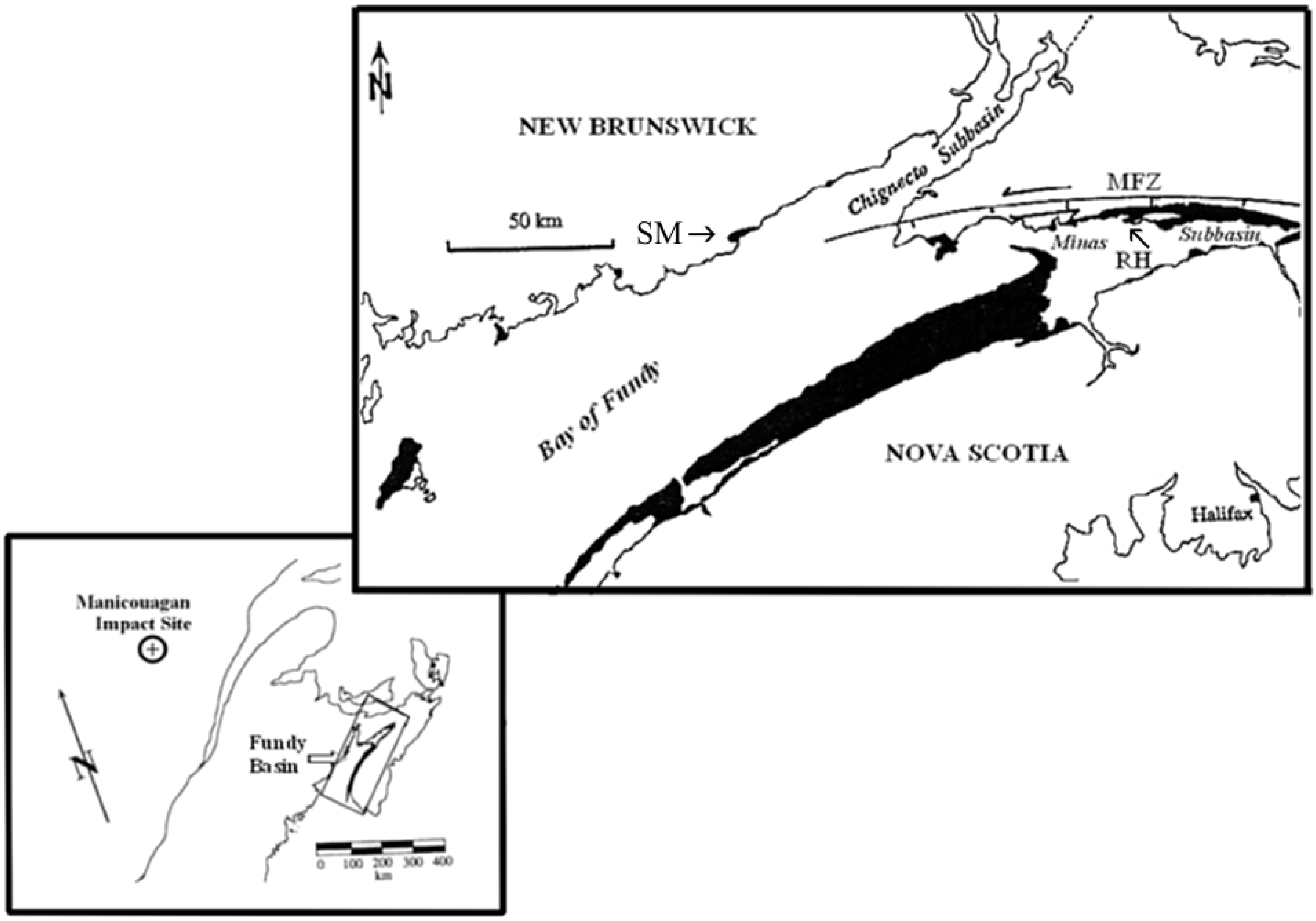

FIGURE 1. Map of the Fundy basin showing outcrops of Triassic and Jurassic formations and major structural elements. MFZ = the Minas Fault Zone, the master fault for the basin; RH=Red Head, the location of features of seismic deformation in the Blomidon Formation described by Tanner (2006); SM=St. Martin's, New Brunswick, the location of the Quaco Formation.

to the indentation surface; however, they also occur randomly distributed through the clasts and with highly variable orientations, including normal to the clast surface (Fig. 5B). Crescentic percussion marks are also present on some clasts, but unlike the blemishes and indentations, these are coated by the hematite stain.

ORIGIN OF THE DEFORMATION FEATURES

Klein (1963) first remarked on the ornamentation of the Quaco cobbles, describing the circular depressions as well as the crescentic percussion marks. The latter he attributed to grain-on-grain impacts during fluvial transport of the sediments, but in explaining the former he invoked the work of the pioneering petrologist Henry Clifton Sorby (1863), who first described the process of pressure solution at grain contacts. Subsequent workers (Nadon and Middleton, 1985; Wade et al., 1996) have followed this interpretation, but none have commented on the fractures that radiate prominently from many of the craters.

Features similar to those on the Quaco clasts were described in the Buntsandstein by Ernstson et al. (2001) and attributed to clast acceleration and concussion during the passage of shock waves produced by the Azuara and Rubielos de la Cérida impacts. Clast collision experiments performed by Ernstson et al. (2001) produced fracturing and spalling similar to that observed in the Buntsandstein clasts, reinforcing their interpretation of an impact-derived seismic shock origin of these features. Comparable features also were described by Bilodeau (2002) in cobbles of the Shinarump Formation near the Barringer (Meteor) Crater, Arizona. Tanner (2003) following Ernstson et al. (2001) and Bilodeau

FIGURE 2. Coastal cliff outcrop of the Quaco Formation conglomerates (overlying the Honeycomb Point Formation). The formation consists primarily of clast-supported cobble conglomerates with interbedded sandstones.

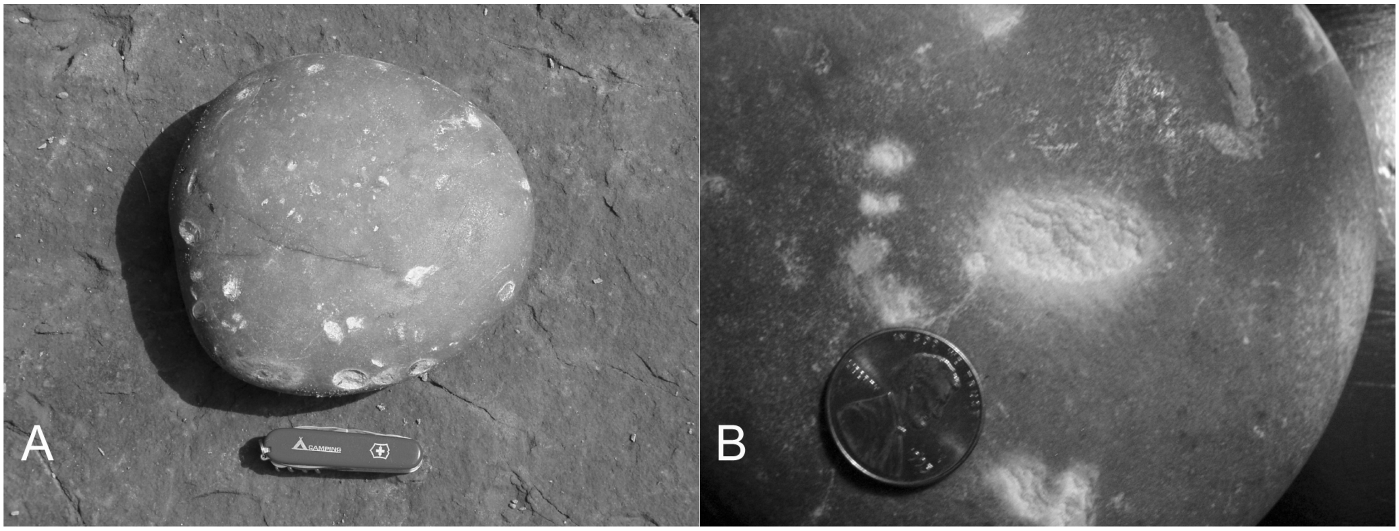

FIGURE 3. Features of Quaco cobble markings. **A**, Markings and depressions occur on multiple sides of most cobbles and vary from near circular to elliptical. **B**, The surfaces of the indentations are often smooth, but also may be hackly. A pale halo surrounds most indentations.

(2002), interpreted the Quaco clast features as produced by concussions during the passage of shock waves from the Manicouagan impact.

Stel et al. (2002), however, argued that the cratering of the Buntsandstein cobbles was a result of mass removal by pressure solution, not shock-generated clast collisions. Indeed, the smooth, bowl-like shape of some indentations, the observable fit of in-situ clasts at points of contact within the depressions, and the presence of microstylolites in the vicinity of the cobble margin (Mosher, 1981) are all consistent with this origin in both the Buntsandstein and Quaco cobbles. In fact, the distribution and wide range of orientations of the stylolites in the Quaco cobbles suggests that instead they are mainly features inherited from the source of the quartzite clasts. Ernstson and Hiltl (2002), in their reply to Stetl et al. (2002), conceded that pressure solution may have occurred in the Buntsandstein cobbles, but noted that Stetl et al. (2002) failed to take into account the experimental work that reproduced the observed fracture patterns, and also that they failed to account for the presence of planar deformation features in grains within the quartzite clasts. Therefore, Ernstson and Hiltl (2002) maintained that impact shock is the best explanation for the deformation features of the Buntsandstein clasts. Chapman et al. (2004) questioned the interpretations of Ernstson et al. (2001), Bilodeau (2002) and Tanner (2003) of an impact origin for the deformation features in the Buntsandstein, Shinarump and Quaco cobbles, respectively. In particular, they noted that the Shinarump conglomerates were at or near the ground surface at the time of the Barringer impact, and therefore not subjected to confining pressure at the time of the impact; thus, they rejected any association between the Shinarump clast features and the Barringer impact. They leave the origins of the markings in the two other formations unresolved, however, stating that further investigation is required.

The craters on the surfaces of the Quaco cobbles are very clearly sites of mass loss, demonstrating that pressure solution operated at points of grain contact. Indeed, the hackly surfaces of some of the craters appear to be stylolitic contacts, as proposed by Stel et al. (2002). Therefore, slow compressive force was responsible for forming the depressions on the cobble surfaces, as originally stated by Klein (1963). Tanner (1994) estimated overburden of the Lower Jurassic McCoy Brook Formation, in the nearby Minas sub-basin at 1 to 2 km, so comparable overburden may be projected in the Fundy sub-basin, the location of the Quaco Formation. Significantly, the entire Fundy basin was subjected to compressive directed stress by basin inversion following the Early Jurassic, associated with the opening of the Atlantic Ocean (Withjack et al., 1995). Hence, there were multiple sources of stress that may have caused pressure solution at point contacts in clast-supported conglomerates in the Fundy basin.

However, features of brittle deformation in the Quaco Formation may instead indicate rapid deformation of the cobbles. The microfractures in the clasts resemble the concussion fractures reported by Kieffer (1971) in quartz grains in weakly shocked rocks of the Coconino Sandstone in the vicinity of the Barringer Crater. The latter are interpreted as tensile fractures formed by the impact of neighboring grains as a shock front passes. Many of the concave open fractures that are common in the Quaco clasts appear to be the result of spalling of the clast surface, as described in the Buntsandstein clasts by Ernstson et al. (2001), and observed in the concussion experiments of these authors.

The Quaco features differ from those reported for the Buntsandstein, most noticeably in the lack of a raised central mound within the indentations. This difference may result from the considerably greater distance between the proposed origin of the shock waves for the Quaco deformation, and the consequent lower collision velocity; particle velocity in a weak pressure wave is inversely proportional to the square of the distance (Melosh, 1989). The resultant velocity apparently was not sufficient to produce the combination of intense Hertzian fracturing and spallation that formed the raised central mounds in the Buntsandstein craters (Ernstson et al., 2001). Nevertheless, the deformational features of the Quaco Formation cobbles appear consistent with an origin by clast collisions during passage of shock waves, although some of these features were undoubtedly later enhanced by pressure solution. The Manicouagan structure, as the closest recognized impact structure that postdates deposition of the Quaco Formation, is the best candidate for generation of the intense shock waves.

DISCUSSION AND CONCLUSIONS

Clearly, impact cratering releases considerable seismic energy; numerical modeling suggests that the Manicouagan impact released energy equivalent to nearly 108 Mt (Norris et al., 2000), some of which undoubtedly generated significant seismic effects over a great area. Assuming 108 Mt of impact energy, and an efficiency of energy conversion (ee) equal to 10-4 (a typical value for fractured crust), the relationship of Toon et al. (1997) predicts an earthquake of magnitude approximately 10 from the Manicouagan impact. The impact site is in rigid (Grenvillean) basement, however, and so ee for the target rocks may be as high as 10-3; therefore the resulting earthquake could have been an order of magnitude higher. Modeling by Boslough et al. (1996) suggests that the amplitude of vertical ground displacement generated by impact seismicity was

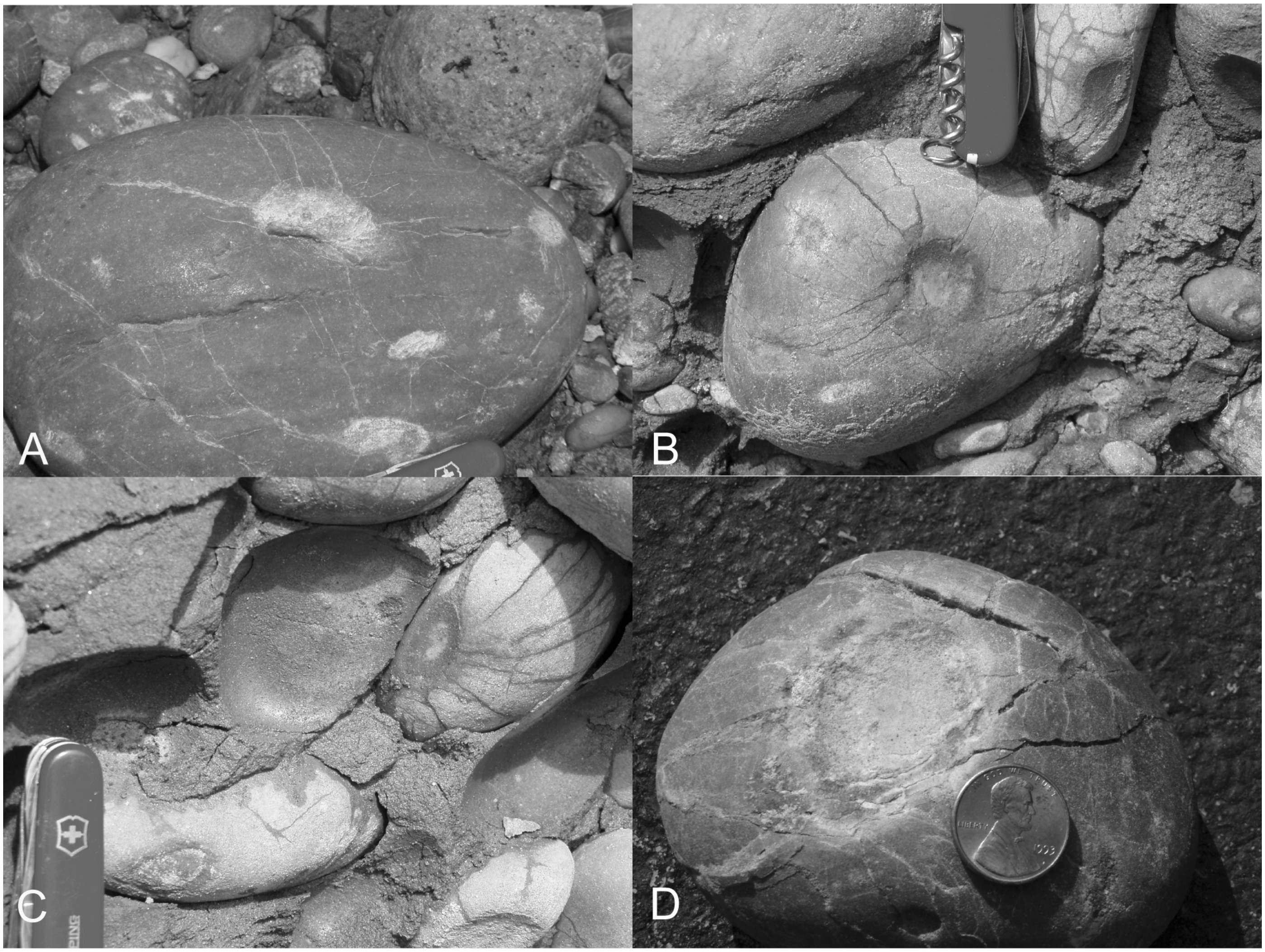

FIGURE 4. Fracturing of the Quaco cobbles. **A**, A radial pattern of fine fractures surrounds many of the indentations. **B**, In some instances, the fractures are deep and penetrate the entire thickness of the clast. **C**, View of clasts in situ, with impression in the sandstone matrix indicating the locations of clasts that have fallen away during weathering. **D**, Open fractures occur where the clast has spalled. Raised surfaces along fractures surrounding the deep indentation indicate intense deformation of the clast.

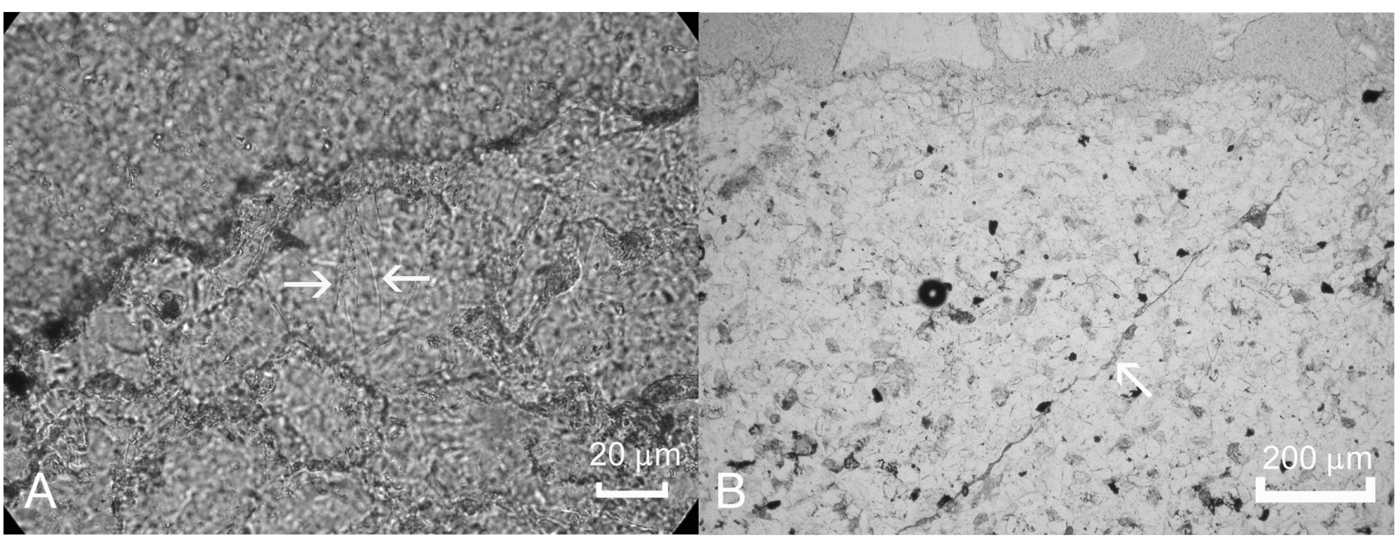

FIGURE 5. Microscopic features of deformed clasts. **A**, Arrows indicate microfractures in grains within the quartzite fabric beneath indented surface (to upper left). **B**, Stylolite cross-cutting quartzite fabric. Indentation surface at top.

greater than 10 m within 100 km of the impact site, and nearly 5 m at a distance of 700 km. Potentially, this seismic energy was sufficient to cause energetic collisions of the clasts in the Quaco Formation.

Of course, the possibility that the Manicouagan impact generated sufficient shock energy to cause concussion fracturing of the clasts in the Quaco conglomerate at points of contact does not translate to indisputable cause and effect. Indeed, an impact origin of the Quaco cobble fractures would seem to require sufficient confining stress (i.e., burial depth) to have produced a rigid clast framework. Therefore the age of the Quaco Formation in relation to the Manicouagan impact becomes an issue. The currently accepted age of the impact places the event during the early Norian stage of the Late Triassic, while the age of the Quaco Formation is constrained by palynology of the overlying Echo Cove Formation as Carnian (possibly Ladinian) or older (Wade et al., 1996). Consequently, the Quaco Formation would have been buried by the Echo Cove Formation and additional younger strata at the time of the Manicouagan impact.

Nevertheless, a significant, perhaps even dominant role in clast deformation must be attributed to clast compression due to confining stress (from overburden) and directed stress (from basin inversion). Conversely, the roles of shock-concussion and compression are not mutually exclusive; as basin inversion long post-dated the passage of shock waves from the Manicouagan impact, concussion fractures initiated by the impact shock could have been enlarged, perhaps greatly, during the compression that caused the pressure solution. In conclusion, while tectonics undeniably played a significant part in producing the features observed in the clasts of the Quaco Formation, the possibility of a role for impact-derived seismicity cannot be ruled out at this time.

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