# A sandstone breccia, formed by quasi-liquid deformation, from the Amadeus Basin, Northern Territory

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**A prominent sandstone breccia crops out in the Pacoota Sandstone, Western MacDonnell Ranges, Northern Territory. The breccia occurs as discontinuous lenses which grade laterally, through incipient breccia and disrupted sandstone beds, into the enclosing sandstone sequence. This sequence consists of interbedded well-sorted silicia-cemented and poorly sorted friable quartzose sandstones; these two sandstone types also constitute, respectively, the clasts and matrix of the breccia. The clasts are rectangular (joint-bounded) and broken rectangular in shape, ranging up to 1 m in length. The matrix is predominantly massive, but convolute bedding is locally present. Similar sandstone breccias are known from three other localities in the region, all at the same stratigraphic level within the Pacoota Sandstone.**

**Petrographic data indicate that the clast sandstone was cemented and strained prior to brecciation, whilst the matrix sandstone retained a largely cohesionless state and failed in a quasi-liquid manner. It is concluded that the brecciation occurred *in situ* at a considerable depth in a sedimentary pile, and resulted from the rotation and fragmentation of joint blocks of silica-cemented sandstone in the interbedded mobile matrix sandstone. Pore-water pressures are thought to have played an important role in the mobilization of the matrix sandstone.**

A prominent sandstone breccia crops out within the basal 10 m of the Pacoota Sandstone at Finke Gorge, Western MacDonnell Ranges, Northern Territory, and is particularly well exposed in the cliff face immediately behind the Glen Helen Tourist Camp (Figure 1). On aerial photographs the breccia is seen to continue along strike for up to 700 m. The breccia was initially described by Mawson & Madigan (1930) and Madigan (1932), but has since received little attention apart from a brief mention by Prichard & Quinlan (1962) and Ranford *et al.*, (1965). Collectively, these brief accounts have proposed three separate origins for the breccia; a sedimentary conglomerate, a tectonic crush breccia and a sedimentary slump breccia. This paper presents the results of a detailed study of this unusual sandstone breccia, and examines the problem of its origin.

## Geological setting

The Pacoota Sandstone is an extensive Cambro-Ordovician marine sequence of well-sorted quartzose sandstone with thinly interbedded siltstone (Wells *et al.*, 1970). This sequence conformably overlies the Cambrian Goyder Formation, a marine sequence of poorly sorted quartzose sandstone, siltstone, dolomite and limestone (Wells *et al.*, op cit.). The contact between these two units is gradational, so that the sandstone breccia which crops out at the base of the Pacoota Sandstone actually occurs in the lithological transition zone where well-sorted quartzose sandstone is interbedded with poorly sorted quartzose sandstone. In the Finke Gorge area, the Pacoota Sandstone forms a prominent strike ridge and dips vertically or very steeply to the south. This ridge forms part of the extensive MacDonnell Ranges which represent the upfolded northern margin of the Amadeus Basin.

Similar breccias, also from the base of the Pacoota Sandstone, were noted by Ranford *et al.*, (1965, p. 24) at two localities to the south (Figure 1); one near Illamurta Yard, and the other on the west bank of the Finke River where it cuts the James Ranges 'A' Anticline. A fourth minor occurrence of similar breccia was observed by the author at Pattalindama Gạp, 4 km south of the Areyonga Native Settlement.

## Description of outcrop

The breccia occurs as discontinuous lenses within an interbedded sequence of cross-bedded, white silicified sandstone and minor brown ferruginous sandstone. The lenses are about 20 cm to 12 m thick, and up to 100 m long. The

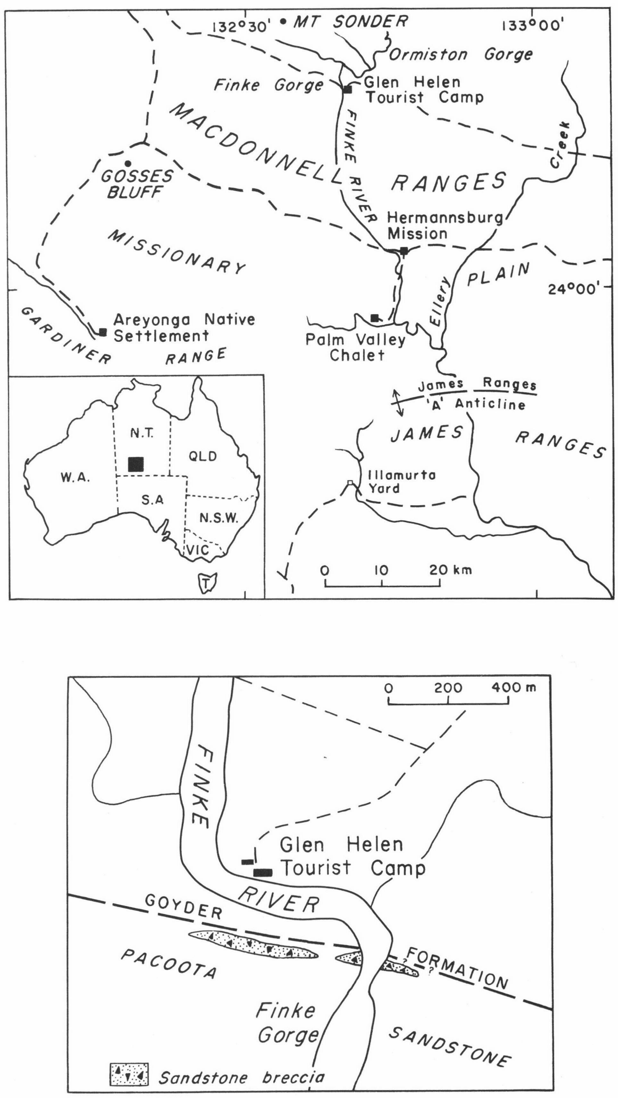


**Figure 1. Locality map with enlarged segment showing the distribution of the sandstone breccia at Finke Gorge.**

**Figure 2.** Disrupted bed of white sandstone within the interbedded white and brown sandstone sequence, Finke Gorge. The bed has been disrupted along joint and bedding planes, and this has caused a slight deformation (convolution) of the lamination in the overlying brown sandstone.

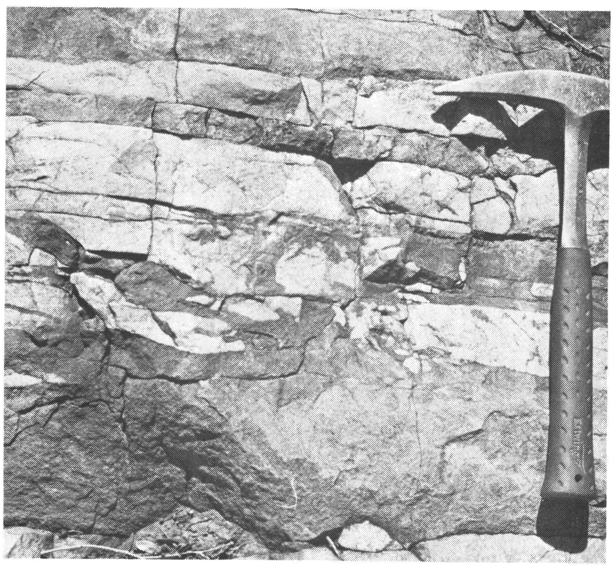

**Figure 3.** Disrupted white sandstone beds and incipient breccia, Finke Gorge.

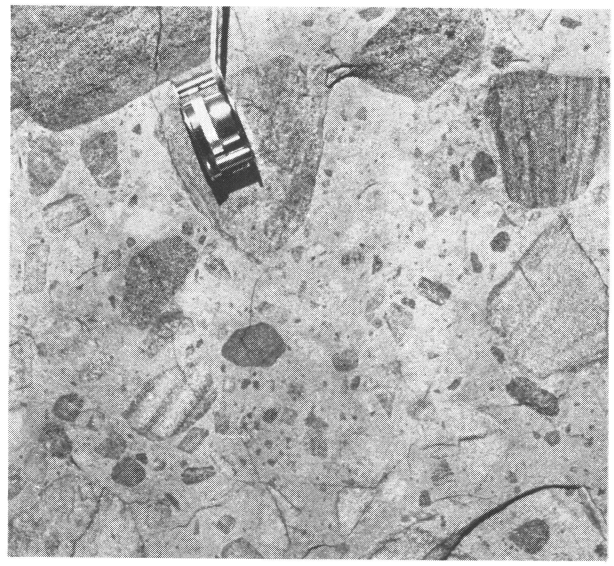

**Figure 5.** Sandstone breccia, Finke Gorge.

**Figure 4.** Small breccia lens enclosed within interbedded white and brown sandstones, Finke Gorge. The breccia to the left of the hammer abuts a joint bounded, white sandstone bed, and contains clasts (rotated blocks and slabs) thought to have been derived from that bed.

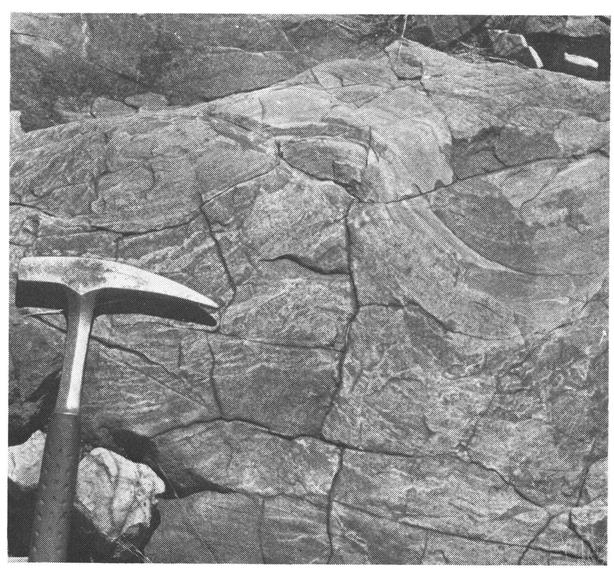

**Figure 6.** Convolute bedding developed in brown (matrix) sandstone which grades laterally into breccia lenses, Finke Gorge.

upper and lower contacts of the breccias are sharp and planar, predominantly conformable with the enclosing sandstone sequence. Locally, however, the breccias partially abut joint faces of white sandstone. The lateral contacts of the breccias are generally irregular, and there is a complete gradation from interbedded white and brown sandstone, to disrupted beds and isolated slabs of white sandstone, to incipient breccias and small breccia lenses (Figures 2, 3, 4). These in turn amalgamate into the larger breccia lenses.

The breccia consists of variable-sized angular clasts of cross-bedded, silicifed, white sandstone set in a matrix of slightly friable brown sandstone (Figure 5). The sandstone composing the clasts and matrix are lithologically indistinguishable from the enclosing white and brown sandstones respectively. The clasts range from less than 1 cm to 1 m in length, and are typically rectangular or broken rectangular in shape. A well-developed stratification parallels and undoubtedly controls their rectangular shape. In places the clasts are closely packed and form a framework, in others they 'float' in the brown matrix sandstone. The matrix sandstone is largely structureless, but irregular convolute bedding is locally present where clasts are sparse (Figure 6).

## Petrography

### *Breccia clasts*

The clasts consist of well to moderately well sorted, fine to medium-grained quartz sandstone (Figures 7, 8). The framework consists of rounded to subrounded quartz together with minor amounts (<1%) of well-rounded tourmaline, zircon, ?epidote, and rare feldspar. The quartz grains are predominantly monocrystalline undulatory quartz, and grain contacts are frequently crushed and sutured. Interstices are filled, or rarely only partially filled, with a quartz cement which occurs as overgrowths in optical continuity with the grains. Fine detrital matrix material is absent.

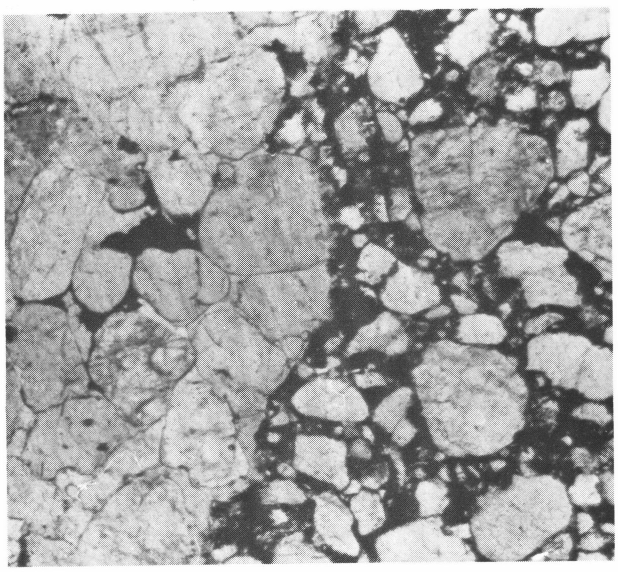

**Figure 7. Contrasting textural maturity of a white sandstone clast (left-hand side) and the brown matrix sandstone. The black interstitial material of the matrix sandstone consists of iron stained silt and clay, whereas the interstices of the white sandstone clast are 'clean' and filled by a quartz cement. Note the broken quartz grains at the margin of the clast. (BMR Slide 75500122C X 40).**

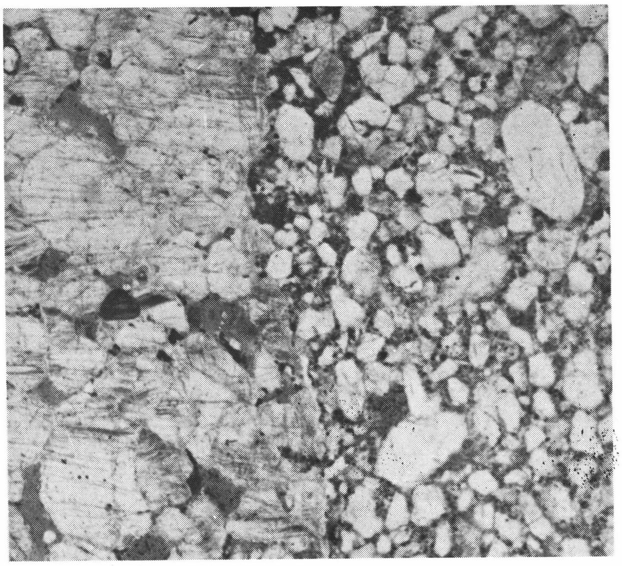

**Figure 8. Strain lamellae within a sandstone clast (left-hand side). Lamellae extend throughout both the grains and the quartz cement of the clast, but stop sharply at the clast/matrix contact. (BMR Slide 75500122E, X 30).**

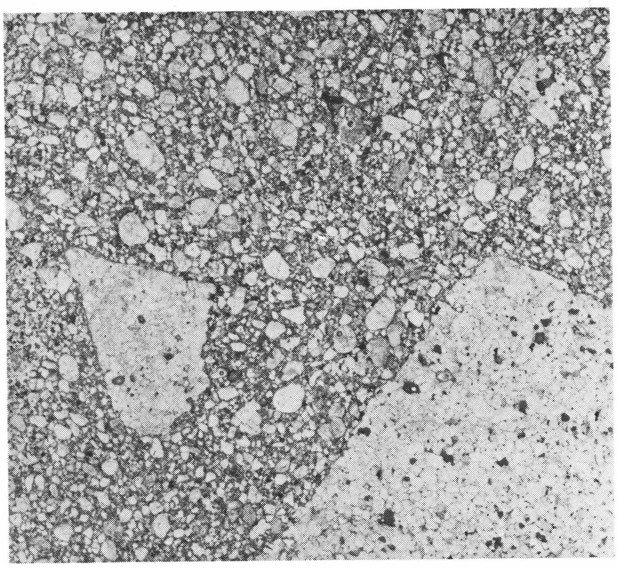

**Figure 9. Sandstone clasts bounded by linear margins (forming rectangular shaped clast) and irregular margins (right hand margin of the clast on the left). Note the marked contrast in grain sorting between the matrix and clast sandstones. (BMR Slide 75500122D X 6.5).**

Many clasts exhibit parallel trains of inclusions (strain lamellae) that extend throughout both grains and overgrowths. In all determinable cases the lamellae parallel bedding traces within each clast. As the orientation of the clasts varies within the breccia, so does the orientation of lamellae. This implies that the white sandstone was cemented and strained prior to its fragmentation and incorporation in the breccia.

The clast margins are linear or irregular (Figure 9). Linear margins cut across both grains and grain overgrowths, and the quartz at the clast margin in finely fractured parallel to that margin. The linear margins commonly define rectangular-shaped clasts and are thought to represent original joint surfaces. Irregular margins, however, are defined and directly controlled by the shape of the constituent quartz grains of the clasts. These margins represent fractures which have selectively followed paths of relatively weak interstitial quartz cement, and grains have been plucked intact from the margin of the clast.

### *Breccia matrix*

The matrix is composed of poor to very poorly sorted quartzose sandstone (Figures 7, 8). The average grainsize of the larger detrital quartz fraction is 0.1-0.2 mm, but there is a complete range from a maximum of 0.75 mm down to silt-size material. Quartz grains are mainly sub-angular, but many rounded, fractured rounded grains (some with fractured overgrowths) and angular grains are present. Minor framework constituents include rounded tourmaline, zircon and ?epidote. Quartz silt and detrital argillaceous material make up 2-15 percent of the sandstone, and a prominent but weak iron-oxide cement is present. Strain lamellae are rarely developed in individual grains, and are randomly oriented from grain to grain. The plasma of the sandstone, fines plus cement, notably lacks an orientation fabric.

Some of the silt-size and larger quartz grains of the matrix sandstone have most likely resulted from the diminution and plucking-off of grains from the white sandstone clasts during brecciation (e.g. the broken rounded grains and the grains with broken quartz overgrowths). The presence of detrital argillaceous material, however, suggests that most of the silt is probably of normal detrital origin.

## Origin

Mawson and Madigan (1930) initially proposed that the breccia represents a coarse conglomerate, but as indicated by Madigan (1932), the angular and monomictic nature of the clasts and the fact that they are indistinguishable from the host sandstone sequence, suggests an *in situ* brecciation. Madigan favoured a crush tectonic origin for the breccia, a proposal later supported by the senior author in Prichard & Quinlan (1962, p. 29). The junior author, however, believed that the breccia was formed by 'slumping before the beds were lithified'. With the discovery of similar breccias at the same stratigraphic level, but at widely scattered localities (Ranford *et al.*, 1965), the sedimentary control on the formation of the breccia was firmly established. These authors supported the proposal of a slump origin. Although the term slump is now generally applied to 'a landslide characterized by shearing and rotary movement of a generally independent mass of rock or earth along a curved slip surface' (Margaret Gary *et al.*, 1972) the author considers that Prichard & Quinlan (1962), and Ranford *et al.*, (1965), applied the term to the breccia at Finke Gorge in the sense of a ?downslope flow or slide of a mass of sediment shortly after its deposition on an underwater slope. This is the sense defined by Challinor (1962), and referred to here as 'slump-like'.

The present author discounts a tectonic origin for the breccia since, in addition to the established stratigraphic control on the formation of the breccia, the orientation of strain lamellae varies from clast to clast (hence straining preceded rather than caused brecciation), and the matrix of the breccia completely lacks a tectonic (e.g. sheared) fabric. Whilst in many regards the breccia shows an affinity to 'slump-like' deposits and mass-flow (Dott, 1963) or sediment gravity flow (Middleton & Hampton, 1973) deposits, collectively referred to here as 'mass-flow' deposits, the following features peculiar to the breccia require further discussion and explanation:

1. The matrix of the breccia is composed of sandstone. Most 'mass-flow' deposits are characterized by a prevalent pelitic matrix (Dott, 1963; Abbate *et al.*, 1970), but some sandy matrix deposits do occur (Leitch, 1969; Dott, 1963). The brown matrix sandstone has locally retained disturbed sedimentary structures (convolute bedding), but otherwise original sedimentary structures have been completely destroyed. Thus failure of the matrix involved a loss of grain cohesion and occurred by means of a grain-by-grain flow, i.e. quasi-liquid deformation of Elliott (1965).

2. The clasts and matrix of the breccia both consist of quartzose sandstone. The clasts and matrix of 'mass-flow' deposits are characterized by a marked contrast in competence at the time of brecciation, and this is typically expressed by a marked contrast between clast and matrix lithologies, such as sandstone and mudstone respectively. The breccia at Finke Gorge, however, has only a subtle distinction between clast and matrix lithologies; both consist of quartzose sandstone and differ only in textural maturity and cementation history. Hence any contrast in competence of the two sand/sandstone types at the time of brecciation was due to the control exerted by textural maturity on cementation.

3. Brecciation occurred *in situ* and involved minimal horizontal and vertical displacements. Individual beds of white sandstone can be traced from the enclosing sandstone sequence into disrupted beds, isolated slabs, rotated blocks and finally scattered clasts. Furthermore, the enclosing sandstone sequence is not disturbed above or below the individual breccia lenses or the whole breccia horizon. Hence the horizontal translation of material evident in 'mass-flow' deposits (typically downslope over considerable distances) did not occur during the formation of this breccia.

4. Brecciation apparently did not occur at or near the sedimentation surface, but rather occurred at a considerable depth in a sedimentary pile. The white sandstone composing the clasts of the breccia was cemented (lithified) and strained prior to disruption and, as indicated by the parallelism of strain lamellae and bedding traces, this straining resulted from vertical compression, i.e. lithostatic loading.

5. The distribution of the breccia is locally controlled by, and many clasts are bounded by, joint surfaces. Again this implies that the white sandstone was competent prior to disruption, and fragmentation was in part controlled by joint patterns developed in the white sandstone.

## Conclusion

An *in situ* disruption of a buried interlayered sand/sandstone sequence is indicated for the breccia; a disruption caused by quasi-liquid deformation of the brown sand layers. The process envisaged is similar to that of the forceful injection of clastic sandstone dykes. The following model is proposed for the genesis of the breccia.

(a) White and brown sands were deposited under alternating conditions of depositional environment and/or source material, so that a sequence of interbedded mature and immature quartz sands resulted.

(b) Initial shallow burial of the sediments was accompanied by selective diagenetic quartz cementation of the highly permeable white sands by the circulation of siliceous groundwaters, whilst the less permeable immature brown sands retained a largely cohesionless state.

(c) Lithostatic loading and compaction of the sedimentary sequence resulted in the straining of the now competent white sandstone beds.

(d) The interlayered competent/incompetent sequence was inherently unstable and eventually failed. The mechanism which triggered this failure is not known. The incompetent brown sands suffered a complete loss of cohesion and failed by a grain-by-grain flow, whilst the competent white sandstone beds failed in a brittle manner and broke into rectangular joint blocks. Rotation and translation of these blocks in the mobile matrix resulted in further fracture and diminution of the white sandstone to form clasts ranging in size from 1 m slabs to individual grains.

(e) Late-state cementation by iron oxide selectively occurred in the previously uncemented matrix sandstone.

The ability of the brown sands to fail in a quasi-liquid manner at such an advanced stage in the burial history of the sediments is poorly understood, but it is suggested that pore-water content may have played an important role. Pore waters would be expected to be a significant component of the porous immature sands and, due to lack of permeability and to capping by the impermeable cemented white sandstones, the water could not escape as overburden pressures increased with burial. Pore-water pressure may have finally approached hydrostatic pressures, destroying grain cohesion. Expanding-lattice clay minerals, capable of assisting failure by expulsion of interlayered water (Powers, 1967) were not detected in the breccia matrix by XRD techniques.

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