stable detrital sand grains. We do not imply that all graywackes are formed in this manner; some may have a primary detrital matrix. However, the importance of diagenesis should not be overlooked as a process that can bring about profound changes in mineralogy and texture, especially in sediment derived from a geochemically immature source area such as the drainage basin of the Columbia River.

5) Several commonly used sandstone classification schemes are based in large part on the amount of matrix present, which is tacitly assumed to be a genetic property related to sorting by the transporting medium. The usefulness of this property is open to serious question unless one can prove that the matrix is of primary depositional origin.

6) It is apparent that eugeosynclinal graywackes encompass a restricted range of chemical compositions equivalent to hydrated (and in many cases oxidized) andesites and dacites. The chemical similarity between andesite-dacite and graywackes is perhaps easily understood in terms of the general petrogenic association of graywackes and intermediate composition volcanic rocks in zones of active tectonism. We suggest that consideration be given to using chemical composition and mineral content as major parameters in classifications of clastic rocks. This would avoid ambiguities arising from reliance on textural features that may be the result of extensive postdepositional modification.

7) Knowledge of the compositions of the fluid phase is critical to understanding the stability relations of the synthesized minerals.

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11 June 1969

Mawson "Tillite" in Antarctica: Preliminary Report of a Volcanic Deposit of Jurassic Age

Abstract. *Reexamination of the Mawson "Tillite" (Jurassic) of Antarctica indicates that the deposit is of volcanic origin and consists largely of both primary and reworked volcanic materials. No evidence diagnostic of a glacial origin was found.*

Gunn and Warren (*1*) in their report on the geology of south Victoria Land, East Antarctica, introduced the name "Mawson Tillite" for a poorly sorted rock supposed to be the product of glacial deposition. (The term tillite will be retained in this report although our work indicates that the rock is not a tillite.) This unit, which crops out on nunataks for over 100 km along the western side of the Transantarctic Mountains, was assigned to the Jurassic System (Fig. 1). The suggested existence of such an extensive glacial deposit of Jurassic age conflicts with some precontinental drift reconstructions of continents of the Southern Hemisphere. For example, the reconstructions of King (*2*) and Runcorn (*3*) place Victoria Land much closer (approximately 40° south latitude) to the Equator during the Jurassic than it is at present. Moreover, glacial deposits of this age have not been reported from any other Southern Hemisphere continent.

A later expedition to south Victoria Land concluded tentatively that the main mass of the tillite (on Allan Nunatak) is a subaerial explosion breccia and volcanic mudflow, although the evidence for such an origin was admittedly only suggestive (*4*). Ballance *et al.* (*4*) also concluded that the origin of the tillite at Carapace Nunatak (Fig. 1) was different from that of the main mass of tillite. It is at Carapace that Jurassic fossils date the tillite (*1, 5*) and, therefore, the age of the main mass of tillite was opened to question.

Our own work centered on three nunataks—Allan, Carapace, and Battlements (Fig. 1). In this preliminary report, the geology of each will be considered in turn.

At Allan Nunatak, Gunn and Warren (*1*) reported over 1300 feet (396 m) of Mawson Tillite resting with disconformity on Permian coal measures assigned to the Beacon group. The Mawson at Allan Nunatak consists of two distinct lithologies. A lower unit, zero to several meters thick, is a mixture of distorted and granulated rocks of the Permian Beacon sandstone and shale, plus fragments of the basalt that intrude the Beacon. The upper unit, which is at least 300 m thick, is distinctly different from the lower one and is a poorly sorted rock partially derived from granulated Beacon rocks but largely from basaltic volcanic material.

Several features indicate that the upper unit is a volcanic mudflow and not a tillite. First, volcanic fragments in the rock are distended and envelop matrix material in a manner that could have been accomplished only while the fragments were hot and mobile. Second, the unit contains abundant, highly indurated, probabably "baked" fragments of Beacon sandstone. Third, thick graded beds on the scale of several tens of meters are present. This latter feature is characteristic of volcanic mudflows (*6*) but is not found in tills (with the possible exception of tills deposited from ice shelves or floating glaciers.) Often the tops of these thick graded beds appear to be worked by water (Fig. 2). The association of these deposits with contemporary igneous activity is further seen by the presence of basalt dikes in the Mawson that have been strung out as if intruded prior to final rest and consolidation of the moving Mawson mass (*4*). A concluding argument against a glacial origin is the apparent lack of striated, grooved, and soled clasts that are almost universally present in till.

The lower unit of the Mawson is gradational from the underlying undistorted Beacon sandstone, through distorted Beacon, to fragments of Beacon in a granulated Beacon matrix. The Beacon sandstone has been distorted, fragmented, and strung out by mass wasting processes on a pre-Mawson surface of great relief. Local disruption of the Beacon sandstone is attributed to the overriding volcanic mudflows.

The Mawson at Allan Nanatak quite clearly postdates the early part of the Late Triassic (see *5*). Although the Mawson rests demonstrably only on Permian strata, the latter are in normal superpositional sequence with 400 m of the overlying Beacon strata of the early Late Triassic less than 1 km away.

Gunn and Warren (*1*) report that at Carapace Nunatak (Fig. 1) there is a section that begins with Beacon sandstone and is overlain by a thick sequence of interbedded tillite containing basalt pillows, tuffaceous tillite, and basalt. The portion of the section above the Beacon is considered by these investigators to be equivalent to the Mawson Tillite sequence elsewhere. Jurassic fossils, more recently identified as Middle Jurassic (*5*), collected from the upper part of the Carapace Beacon sequence were therefore considered to date the Mawson Tillite as Jurassic. Ballance *et al.* (*4*), however, considered that the Carapace "tillite-volcanic" section is of different origin from the tillite sequence at Allan Nunatak (Fig. 1).

Carapace Nunatak in Victoria Land is perhaps the key to the stratigraphy of those rocks younger than the Beacon. Past workers (*1, 4*) assigned the volcanic sandstone section at the base of the Carapace sequence to the Beacon. Our interpretation of the sequence at Carapace Nunatak suggests that the lowest portion of this Beacon sandstone unit should in fact be assigned to the tillite-volcanic sequence, since it consists of rock indistinguishable from the Mawson Tillite of Allan Nunatak. The upper portion of the section at Carapace Nunatak consists of sandstone and conglomerate reworked from older or contemporaneous but distant volcanic mudflows. Similar reworked material is present locally at Allan Nunatak.

In the upper section at Carapace the "tillite with pillows" of Gunn and Warren (*1*) is a mixture of basaltic breccia and basalt pillows. Newly found exposures on the northwest edge of the nunatak display pillows at the base of this unit that are intimately involved with pond deposits containing large crustaceans, insects, and plants. The "tuffaceous tillites" of Gunn and Warren (*1*) higher up in the section are graded and reworked volcanic mudflow deposits similar to those at the base of the Carapace section and at Allan Nunatak.

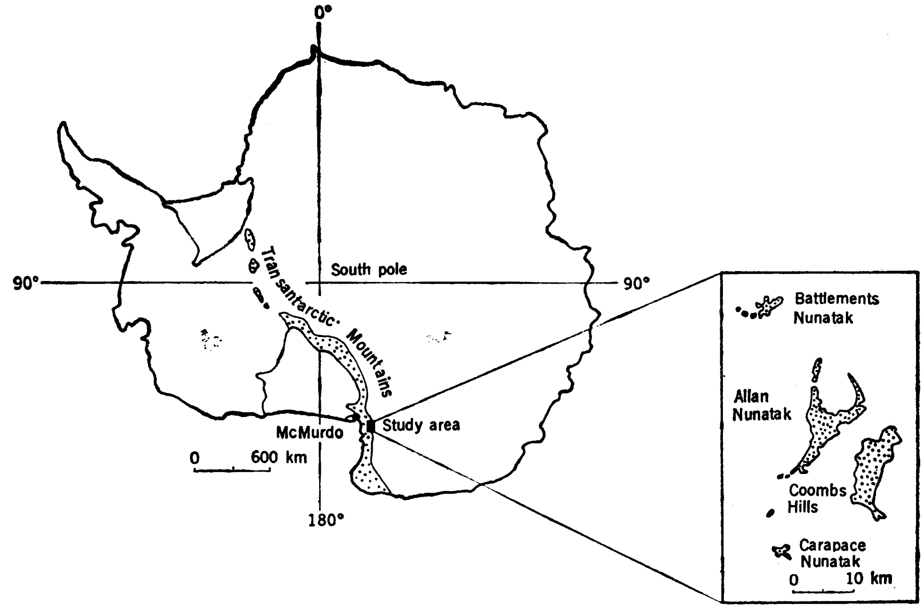

Fig. 1. Index map of Antarctica showing location of areas discussed.

The western part of Battlements Nunatak (Fig. 1) consists of basalt flows interbedded with approximately ten volcanic mudflows similar to those at Allan and Carapace nunataks. Several units of water-worked volcanic sandstone derived from volcanic mudflows similar to that at Carapace are also interbedded with the basalt flows. These range in thickness from 1 to approximately 15 m. One outcrop revealed a unit of Mawson approximately 30 m thick intrusive into flow-banded basalt. This is interpreted as an explosion breccia vent or conduit of the Mawson Tillite. A thickness of at least 100 m of basalt and mudflows is present. The eastern part of Battlements consists of undated Beacon sandstone and shale hornfelsed and intruded by basalt.

In conclusion, our work disclosed no evidence supporting a glacial origin of the Mawson Tillite. To the contrary, the evidence indicates that the main mass of the Mawson Tillite is of volcanic origin, probably explosion breccias emplaced by gravity flow after original extrusion. Evidence of reworking of the tops of these flows by water is abundant. Furthermore, the bedded volcanic sandstone at Carapace Nunatak is not typical of the quartzose sandstone of the Beacon group. This "Beacon" sandstone is probably a thick section of reworked volcanic mudflow material. The rocks at Carapace Nunatak and those assigned to the Mawson at Battlements and Allan nunataks comprise a very thick complex of basalt, explosion breccia, volcanic mudflows, and volcanic sandstone unconformably overlying the Beacon group.

The interbedded fossiliferous pond deposits of Middle Jurassic age at Carapace Nunatak (*1, 5*) date this volcanic complex with reasonable accuracy throughout the area considered. However, the base of the complex at Allan Nunatak could be as old as latest Triassic since it is probably lower in the section than the rocks at Carapace and must be younger than the

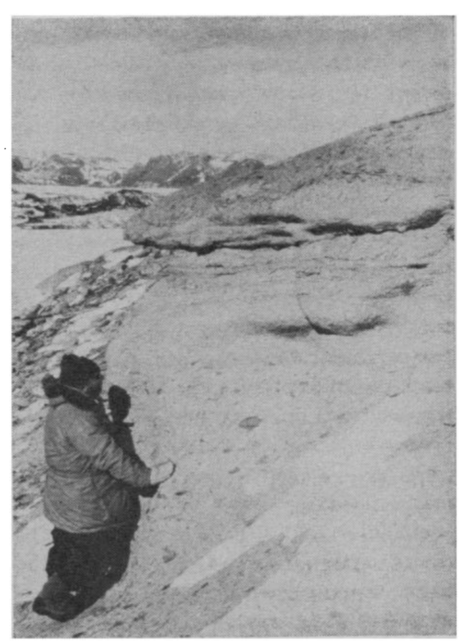

Fig. 2. Graded bedding and stratification within the Mawson Tillite at Allan Nunatak.

youngest Beacon rocks present, which are most likely of early Late Triassic age. Jurassic time in this part of East Antarctica was one of intense volcanism, not glaciation.

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Buoyancy and Solar Spin-Down

Abstract. *The transition of a cylinder of water with a vertical density gradient between convective and viscous spin-down occurs near the point at which the maximum buoyancy force equals the radial pressure gradient that is driving the convection. A similar analysis applied to the sun shows the maximum buoyancy force to be 1500 times the convective force. A rapidly rotating solar interior would not be damped by large-scale convection.*

The rapidly rotating solar interior proposed as the cause of the oblateness observed by Dicke and Goldenburg (*1*) has been criticized by Howard *et al.* (*2*) on the ground that such a distribution of solar angular momentum would be unstable with respect to large-scale convection. This convection, driven by pressure gradients along the boundary of the rotating region, would quickly damp out any rotation of the interior relative to the surface. McDonald and Dicke (*3*) have countered this objection by pointing out that a density gradient in the direction of the gravitational field will produce buoyancy forces that tend to stop convection. In a laboratory experiment in which an axially rotating cylinder of water was slowed down (*3*), they have demonstrated that such a density-stratified fluid requires a much longer spin-down time. Their result indicates that convection can be prevented by a density gradient. Dicke (*4*) also demonstrated that solutions to mathematical models not involving convection do exist and that a uniformly rotating core with a differentially rotating shell is such a solution.

We have repeated the experiment of McDonald and Dicke and have confirmed their results. We varied the height of the liquid in the cylinder to determine the transition between the convective spin-down which occurs for uniform fluids and the viscous spin-down which occurs for density-stratified fluids. (By convective spin-down we refer to the meridional circulation of the fluid which results in rapid damping of the azimuthal circulation due to bulk transfer of angular momentum. The viscous spin-down process consists of purely azimuthal flow which is damped by the internal friction of the fluid.) The transition occurs near the point at which the buoyancy force F_B, calculated by integrating the difference between the local density ρ and the maximum density ρ_0 from the top to the bottom of the liquid, is equal to the convective force F_C. The convective force is obtained by integrating the pressure gradient along the radius of the cylinder.

$$F_B = \int_H^0 (\rho - \rho_0)\, g\, dz \qquad (1)$$

where g is the acceleration of gravity;

$$\rho = \rho_0 - [(\rho_0 - \rho_{H_2O})/H]z \qquad (2)$$

ρ_{H_2O} is the initial density at the top of the cylinder, taken to be that of distilled water; H is the height of the cylinder of fluid; and z is the vertical coordinate measured from the bottom.

$$F_C = \int_0^R \rho_0 r\, \Delta(\omega^2)\, dr \qquad (3)$$

where R is the radius of the cylinder, and r is the radial coordinate measured from the axis. In Eq. 3, the pressure gradient has been set equal to the difference between the centrifugal force in the boundary layer and the centrifugal force in the bulk liquid; consequently, $\Delta(\omega^2)$ may be taken as the difference between the squares of the initial and final velocities of the turntable.

The experiment is performed by placing a cylindrical container of fluid on a turntable, allowing it to come to equilibrium, and then introducing a differential rotation by slowing down the container. The convective currents arising in such a system are called "Ekman pumping" (*5*), and the movement of tea leaves into the center of a cup of stirred tea is an example of this phenomenon. Our experiment, although essentially the same as that of McDonald and Dicke (*3*), was designed to determine whether the actual density gradient inside the sun is large enough to suppress convection. To this end, we were interested in verifying a simple force-balance argument which would determine quantitatively the transition point between convective and viscous spin-down.

Stock solutions of $Cu(NO_3)_2$ (1.20 g/cm^3) were diluted with distilled water to produce solutions with densities of 1.15, 1.10, 1.05, and 1.025 g/cm^3. Density-stratified solutions with values of ρ_0 that ranged from 1.2 to 1.025 g/cm^3 were compared with uniform-density solutions of the same mean density. Changes in the angular velocity ranged from 0.15 to 4.91 rev/min with all runs having an initial angular velocity of 18.7 rev/min.

The density-stratified fluids were prepared by pouring the fluids into the container over a small hollow petri dish lid that was allowed to float in the fluid. The density variation could thus be established in layers and then carefully mixed by hand to provide a uniform density gradient. The actual density profile was measured before and after each run with a photometer that was driven slowly down into the fluid at a constant rate. The photometer was calibrated directly against stock solutions so that the optical transmittance and consequently the density were given as functions of z. Density profiles approaching linearity were established before each run. The process of bringing the container up to its equilibrium velocity and stopping generally degraded the profile but did not destroy it. The average density gradient was normally reduced by about 50 percent. The density-stratified fluids were quite stable against diffusion. Once prepared, they would last many hours if left undisturbed.

The only fundamental difference between our experimental setup and that of McDonald and Dicke was the alignment with the gravitational vertical. They maintained the axis of the container parallel to the gravitational vertical to within 1 second of arc to eliminate the small constant-velocity residuals which are established in the fluid if the container is tilted. In our experiment, the alignment was maintained to within 10 seconds of arc, with the velocity residuals measured immediately before a run and added algebraically to the motion of the fluid.