

structure very close to the right age, but the rocks excavated at the crater appear to be a likely source for the shocked grains as well as most other grains lacking observable shock lamellae in the upper stratum.

The occurrence of two impacts separated in time by at least part of a growing season appears to be most readily explained if the Earth intercepted a compact comet stream at the end of the Cretaceous [20]. In repetitive passes through the stream, the Earth may have encountered more than two crater-forming projectiles and may have swept up substantial amounts of cometary material that did not produce craters. The peak Ir abundance, which occurs in the upper stratum, may reflect a somewhat protracted accumulation of cometary material. Iridium is relatively low in abundance in the boundary claystone, possibly as a consequence of blowoff and escape of the vaporized projectile that formed the great Chicxulub impact structure [cf. 21].

A comet stream is most likely to have been formed by breakup of a large Sun-grazing comet. Reexamination of the flux of active and extinct Earth-crossing comets suggests that collision of periodic comets accounts for about 25% of the terrestrial impact craters larger than 20 km in diameter. Periodic comets initially on orbits with inclinations near 90° become Sun grazers [22]. More than one-fifth of the Earth-crossing periodic comets probably become Sun grazers that are subject to tidal disruption.

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centrated along its base; locally, however, they are restricted to centimeter-thick lenses of pure spherules along a single horizon in the argillite close beneath the turbidite. The total volume of preserved spherules is estimated at 8×10^7 m³. Assuming an original specific gravity of 2.5, typical of silicate glass, the lower limit of the total original mass of spherules is about 1.7×10^{14} g.

In the northeastern part of the Hamersley Basin, similar spherules again occur at only one horizon, but here they are a minor constituent of a dolomitic debris-flow deposit 9.9 to 22.7 m thick known as the dolomixtite layer. The dolomixtite layer occurs in the Carawine Dolomite, which is stratigraphically equivalent to the Wittenoom Formation [3]. Moreover, paleocurrent data from closely associated carbonate [4,5] and volcanoclastic [6,7] turbidites indicate the spherule marker bed was deposited in deeper-water paleoenvironments than the dolomixtite layer. Therefore, the dolomixtite layer is believed to be a proximal equivalent of the spherule marker bed. In addition to spherules, the dolomixtite layer contains particles that also consist of K-feldspar, but are larger than the spherules (up to 11 mm across) and have much more internal heterogeneity. Some display internal flow banding or schlieren, while others contain typical spherules as inclusions. These larger particles are in the size range of true tektites, but ablated forms have yet to be observed.

Based on their similarity to microtektites and mikrokrystites in shape, size, and internal textures, and their occurrence as a very thin layer over a large area, the spherules are interpreted as droplets of silicate melt that were generated and dispersed across the Hamersley Basin by a major bolide impact. The mass of the spherules preserved in the Hamersley Basin is of the same order of magnitude as the estimated masses of microtektite glass in major Cenozoic strewn fields, despite the fact that the spherules currently cover an area that is 2 to 3 orders of magnitude smaller. The layers that host the spherules are interpreted to be the deposits of a major sediment gravity flow that exhumed and redeposited most of the spherules after shallow burial, although the flow is not believed to have been a direct result of the proposed impact. The internal textures of the spherules suggests the target rocks were mafic in composition, but the presence of trace amounts of microcline and quartz crystals in both the spherule marker bed and dolomixtite layer suggests some continental basement rocks were also present in the target area. Given this, plus the fact that the spherules and related particles are largest in the northeastern corner of the Hamersley Basin, the most likely site for the proposed impact would have been in the early Precambrian ocean close to the northeastern edge of the Pilbara Craton.

Another thin horizon in the overlying Brockman Iron Formation contains spherules that again consist largely of K-feldspar and have internal textures strikingly similar to those of the Wittenoom Formation and Carawine Dolomite. They differ in being slightly larger on average (up to 1.8 mm) and extensively replaced by iron-rich minerals (particularly stilpnomelane) as they are hosted by iron formation rather than argillite. This horizon is about 250 m higher stratigraphically and persists laterally for at least 30 km. The close resemblance of these spherules to those of the Wittenoom Formation and Carawine Dolomite suggests they also originated as impact melt droplets, even though they are admixed with volcanoclastic detritus. Using the sedimentation rate of 3-4 m/m.y. typical of the Hamersley Group [8], the stratigraphic separation between the two suggests that a second major impact occurred near the Hamersley Basin after a time interval of about 75 m.y. elapsed. This suggests the record of impacts in early Precambrian strata is richer than is generally appreciated.

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 GEOLOGICAL EVIDENCE FOR A 2.6-Ga STREWN FIELD OF IMPACT SPHERULES IN THE HAMERSLEY BASIN OF WESTERN AUSTRALIA. Bruce M. Simonson, Geology Department, Oberlin College, Oberlin OH 44074, USA. ²⁰⁵⁷⁸⁹⁴⁰

Sand-sized spherules up to 1.7 mm across with spherulitic, vesicular, and other crystalline textures that consist mainly of K-feldspar help define a unique horizon in the well-preserved 2.6-Ga Wittenoom Formation in the Hamersley Basin of Western Australia [1,2]. This layer, informally known as the spherule marker bed, is nowhere thicker than about 1.3 m, yet it persists for more than 300 km across the basin, blanketing an area of at least 13,700 km². Sedimentological evidence indicates the layer is a single turbidite, and the spherules are a minor constituent that are usually con-

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SAR IN SUPPORT OF GEOLOGICAL INVESTIGATIONS OF THE SUDBURY STRUCTURE. V. Singhroy¹, R. Mussakowski², B. O. Dressler³, N. F. Trowell³, and Richard Grieve⁴, ¹Canada Centre for Remote Sensing Department of Energy, Mines and Resources of Energy, Mines and Resources, Canada, ²Provincial Remote Sensing Office, Ontario Ministry of Natural Resources, Canada, ³Ontario Geological Survey Ministry of Northern Development and Mines, Canada, ⁴Geological Survey of Canada, Department of Energy, Mines and Resources, Canada.

Imaging radar is an important contributing source of information for a range of geological problems and environments. Airborne SAR and ERS-1 data integrated with other geoscience datasets are being used in an attempt to characterize the crustal fracturing associated with the Sudbury structure. This presentation highlights examples of integrated and composite images aimed at facilitating the interpretation of the Sudbury structure. This work is the result of an ongoing cooperative multidisciplinary SAR study of the basin carried out by the Canada Centre for Remote Sensing, Ontario's Provincial Remote Sensing Office, the Ontario Geological Survey, and the Geological Survey of Canada.

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VISCOSITY DETERMINATIONS OF SOME FRICTIONALLY GENERATED SILICATE MELTS: IMPLICATIONS FOR SLIP ZONE RHEOLOGY DURING IMPACT-INDUCED FAULTING. John G. Spray, Department of Geology, University of New Brunswick, Fredericton, New Brunswick, Canada.

Analytical scanning electron microscopy, using combined energy dispersive and wavelength dispersive spectrometry, has been used to determine the major-element compositions of some natural and artificial silicate glasses and their crystalline equivalents derived by the frictional melting of acid to intermediate protoliths. The major-element compositions are used to calculate the viscosities of their melt precursors using the model of Shaw [1] at temperatures of 800°-1400°C, with $Fe^{2+}/Fe_{tot} = 0.5$ and for 1-3 wt% H₂O. These results are then modified to account for suspension effects (i.e., the presence of mineral and rock clasts) in order to determine effective viscosities.

The critical factors in controlling the viscosities of the silicate melts are SiO₂ and H₂O contents and temperature, as has been well established for silicate melts of magmatic origin. Additionally, for fault-generated melts, the effects of shear thinning can reduce the viscosity to a significant degree. At 1200°C, the viscosities range from 7 p for the more basic melt sample (40 wt% SiO₂) to 1 × 10⁵ p for the more acid melt sample (64 wt% SiO₂). These viscosities are

low and indicate that at least the friction melt derived from the more basic protolith would have been highly fluid within the slip zone during displacement. The effects of shear thinning at very high strain rates would reduce these viscosities even further.

Where friction melts are generated during coseismic slip (to form pseudotachylites) this implies that the melt may help to lubricate the sliding interface and dissipate stored strain energy. These results are contrary to the views of earlier workers, who suggested that any melts generated by frictional heating would possess high viscosities and so inhibit slip. Part of this inference was based on the erroneous assumption that pseudotachylite generation involved the bulk fusion of wallrocks. Although a pseudotachylite matrix plus clasts has a very similar chemistry to the wallrock lithology, the matrix typically possesses a more basic chemistry and hence, due to its lower SiO₂ content, a significantly lower viscosity than that of its protolith. On the other hand, smaller entrained clasts (<1 cm diameter) are typically felsic and dominated by quartz.

These results have implications for the generation of pseudotachylitic breccias as seen in the basement lithologies of the Sudbury and Vredefort structures and possibly certain dimict lunar breccias. Many of these breccias show similarities with the more commonly developed pseudotachylite fault and injection veins seen in endogenic fault zones that typically occur in thicknesses of a few centimeters or less. The main difference is one of scale: Impact-induced pseudotachylite breccias can attain several meters in thickness. This would suggest that they were generated under exceptionally high slip rates and hence high strain rates and that the friction melts generated possessed extremely low viscosities.

Reference: [1] Shaw H. R. (1972) *Am. J. Sci.*, 272, 870-893.

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THE LARGE IMPACT PROCESS INFERRED FROM THE GEOLOGY OF LUNAR MULTIRING BASINS. Paul D. Spudis, Lunar and Planetary Institute, Houston TX 77058, USA.

The nature of the impact process has been inferred through the study of the geology of a wide variety of impact crater types and sizes. Some of the largest craters known are the multiring basins found in ancient terrains of the terrestrial planets [e.g., 1]. Of these features, those found on the Moon possess the most extensive and diverse data coverage, including morphological, geochemical, geophysical, and sample data. The study of the geology of lunar basins over the past 10 years [2-4] has given us a rudimentary understanding of how these large structures have formed and evolved.

→ Basin Morphology: Basins on the Moon begin to form at diameters of about 300 km, the 320-km-diameter Schrodinger being an example [5,6]. At these diameter ranges, only two distinct rings are apparent; the transition diameter at which multiple rings appear is uncertain, but appears to be between 400 and 500 km in diameter [6]. Above these diameters, basins possess multiple rings, as few as three and as many as seven [1,5,6]. In every basin, one ring appears to be very prominent and is believed to correspond structurally to the topographic rim of complex craters. This ring has various names (basin rim of [5], Ring IV of [6], MOR of [7]), but corresponds to the Cordillera ring of the Orientale Basin. Rings inside and outside this ring are recognized, each having distinct morphology. Basin inner rings tend to be clusters or aligned segments of massifs, arranged into a crudely concentric pattern; scarp-like elements may or may not be present. Basin outer rings tend to be much more scarp-like and massifs are rare to absent. Within a certain subset of basins on the Moon (e.g., Crisium [8], Humorum [9]), the main topo-