rocks) in the northwest. Structural information suggests that the structure is open to the southeast. From this it may be inferred that contractional forces acted from south to north.

In conclusion, the structural studies coupled with the geophysical results suggest that the Vredefort structure was produced by subhorizontal forces. No macro- or megascopic structural deformation that could be related to a 2-Ga central catastrophic event could be identified.

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INTRUSIVE ORIGIN OF THE SUDBURY IGNEOUS COMPLEX: STRUCTURAL AND SEDIMENTOLOGICAL EVIDENCE.

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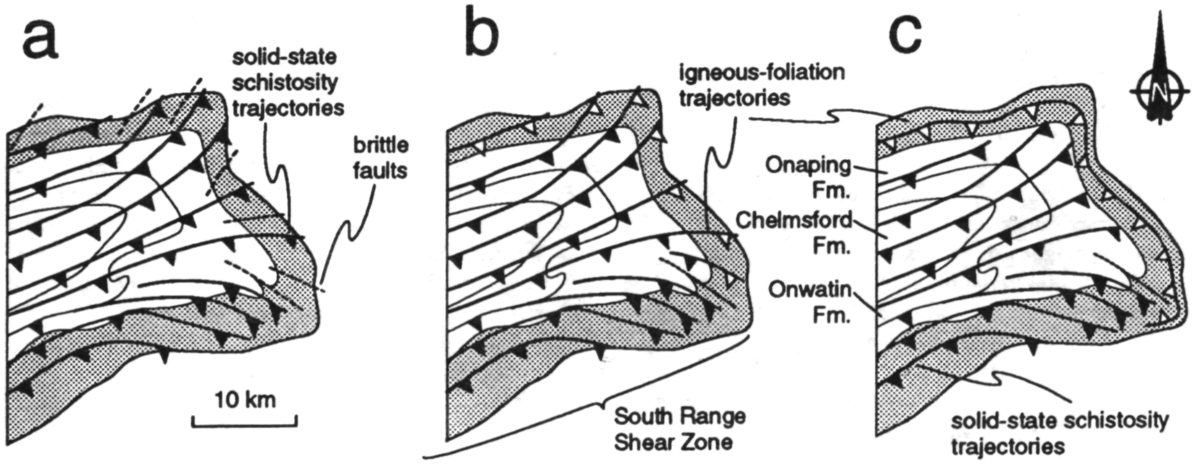
In recent years, many geoscientists have come to believe that the Sudbury event was exogenic rather than endogenic [1–3]. Critical to a recent exogenic hypothesis is the impact melt origin of the Sudbury Igneous Complex (SIC) [3]. Such origin implies that the SIC was emplaced before deposition of the Whitewater Group, in contrast to origins in which the SIC postdates the lithification of the Onaping Formation. Structural and sedimentological evidence is summarized herein that supports an intrusion of the SIC after lithification of all Whitewater Group strata, and conflicts with the hypothesis advanced by Grieve et al. [3].

The SIC has the map pattern of an oval ring, and dips inward at the present erosion level. The bilobate eastern part of the SIC resembles fold interference patterns figured by Stauffer and Lisle et al. [4,5], yet the granophyre, gabbro, and norite have undergone no solid-state deformation at most localities. This rules out the foliation pattern in Fig. 1a, which is consistent with the impact-melt hypothesis [3]. If the SIC acquired its foldlike shape during or immediately after emplacement, metamorphic-foliation trajectories in the Onaping Formation would continue as igneous-foliation trajectories into the granophyre, gabbro, and norite (Fig. 1b) [6,7]. This is true in the northeast lobe of the SIC, and rules out the possibility of post-fold sheet injection (Fig. 1c) [8].

The Chelmsford Formation, a turbidite deposit with nearly invariant bed thickness (1.2 m average), detrital composition, and high sand/mud ratio, was deposited by uniformly southwest-directed currents [9,10], and was part of a very large nonchannelized foreland basin turbidite system [11]. The lack of facies change in the northwest-southeast direction implies that the preserved Chelmsford strata were far from the original foreland basin margin or from a site of syndepositional tectonic disturbance. This suggests that the South Range Shear Zone [12], which probably had a geomorphic expression at surface, postdates the Chelmsford Formation and its lithification.

The combined sedimentary and structural evidence constrains the time of emplacement of the SIC and its consolidation. Turbidite complexes have sedimentation rates of 100–1000 m/m.y., with foreland basin-fill systems typically ranging 400–900 m/m.y.



Pre-fold emplacement of the Sudbury Igneous Complex:

Solid-state strain whithin the SIC with schistosity trajectories concordant to that of the sedimentary core

Syn-fold emplacement of the Sudbury Igneous Complex:

SIC with igneous-foliation trajectories concordant to schistosity trajectories of the sedimentary core

Post-fold emplacement of the Sudbury Igneous Complex:

SIC with igneous-foliation trajectories concordant to intrusive contacts

Fig. 1. Eastern Sudbury structure: SIC (shaded), Whitewater Group (white).

[13–15]. The minimum stratigraphic thickness of the Chelmsford Formation is 600 m, so that the depositional time required is >1 m.y. The fastest deposition rate of hemipelagic deposits is 300 m/m.y., so that 600-m thickness of the Onwatin Formation corresponds to >2 m.y. [15], and possibly as much as 6 m.y. (D. G. F. Long, personal communication, 1992). This amounts to a time interval of at least 3 m.y. between the Sudbury event and the tectonic deformation of the Whitewater Group and the SIC.

If the SIC was formed as an impact melt, the sequence of events proposed herein requires the SIC deform in an unconsolidated state, 3–10 m.y. after its intrusion. Plutons emplaced at mid to upper crustal levels are thought to take 1–10 m.y. to cool to the ambient wall-rock temperatures; however, consolidation of a pluton takes a fraction of that time [7]. Impact melt sheets of the size of the Igneous Complex would crystallize well within 1 m.y. of their formation [3]. This duration is shorter than the time interval required for the deposition of the Onwatin and Chelmsford Formations. Together with the evidence for magmatic folding of the SIC, this time constraint renders the impact melt hypothesis of the SIC untenable.

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ENHANCED MAGNETIC FIELD PRODUCTION DURING OBLIQUE HYPERVELOCITY IMPACTS. D. A. Crawford and P. H. Schultz, Department of Geological Sciences, Brown University, Providence RI 02912, USA.

The natural remanent magnetization of the lunar surface as displayed in returned lunar samples and the data returned by the Apollo subsatellite magnetometer has an unexpectedly high magnitude and exhibits spatial variation at all scales. The origin of the lunar remanent fields may be due to crustal remanence of a core dynamo field occurring early in lunar history prior to extensive modification by impact [1] or remanence of transient fields, particularly associated with impacts, occurring on a local scale throughout lunar history [2–5]. The presence of an early core dynamo field would have strong consequences for the formation and early evolution of the Moon, yet to deconvolve the role that an internally generated core dynamo field may have had, it is necessary to understand how the magnetic state of the lunar surface has developed through time. Impact-induced magnetism may be an important component of the present magnetic state of the lunar surface.

New theoretical considerations suggest that transient magnetic fields within plasma produced by hypervelocity meteorite impacts may have greater significance at larger scales than previously thought [6]. Self-similar, one-dimensional solutions for the evolution of the magnetic field and electron energy within impact-generated plasma demonstrate that the peak magnetic field strength may only weakly depend on projectile size. Because the ratio of projectile size to crater size increases at larger scales for gravity-limited growth, the peak strength of transient impact-generated magnetic fields probably increases with increasing crater size at the same diameter-scaled distance. A conservative estimate (from extrapolated experimental data) for 10–100-km craters formed by vertically incident meteorite impacts at 25 km/s predicts magnetic field strengths of at least 0.03–0.1 G for several minutes or more [6]. This is within the range of paleointensity values determined for certain relatively young (3 Ma to 1.5 Ga) lunar samples [7–9] and more generally may help account for the lunar magnetic record during the last ~3.5 b.y. Recently acquired experimental evidence suggests that impact at oblique incidence may further enhance magnetic field production by as much as an order of magnitude.

Experimental investigations of magnetic field generation and evolution during hypervelocity impacts have been conducted at the NASA Ames Vertical Gun Range, Moffett Field, California [10–12]. The vertical gun is a two-stage hydrogen light gas gun capable of launching macroscopic projectiles at up to 7 km/s with the angle of impact varying from nearly horizontal to vertical in increments of 15°. The large impact chamber, which can be evacuated to less than ~1 Torr, is large enough to accommodate, surrounding the impact point, a mu-metal shield that reduces the 35-μT terrestrial magnetic field to 450 ± 80 nT—comparable to lunar surface field strength.

Impacts of aluminum projectiles into powdered dolomite ($Mg_{0.5}Ca_{0.5}CO_3$) targets readily produce a self-luminescent, slightly ionized vapor cloud that we infer to be the source of impact-generated magnetic fields [3,6]. Oblique impacts demonstrate enhanced vapor yield producing a vapor cloud that retains a portion of the impactor momentum with a leading edge that travels downrange at a significant fraction of the impact velocity [13].

The configuration and duration of impact-generated magnetic fields observed during laboratory hypervelocity impacts are strongly dependent on impact angle (Figs. 1–3). Magnetic search coil data from many experiments under identical impact conditions were combined to produce the plots shown. The observed magnetic fields exhibit a regular transition from a cylindrically symmetric field configuration at vertical incidence to a strong bilaterally antisymmetric field configuration at high obliquity (Figs. 1 and 2). The stronger magnetic fields observed during oblique impacts (see Fig. 3) could result simply from the close proximity of impact-generated plasma to the target surface, from a fundamental change in the field production mechanism within the plasma or from increased vaporization [13] yielding a greater volume of magnetized plasma; however, this could not be resolved with the data obtained. In addition to impact angle, experiments demonstrate that the configuration and duration of impact-generated magnetic fields are dependent on impact velocity and projectile/target composition [11].

A remnant of the impact-generated magnetic field could be induced within the target material during passage of the impact-induced shock wave [14,15] or by cooling through the Curie point of small portions of impact melt or hot target material. During oblique impacts, spalled fragments of the projectile may impact further downrange at hypervelocities [16], thereby inducing a shock and/or thermal remanence significantly offset from the crater rim. Because of these dependencies, remnant impact-generated magnetic fields could be a useful geophysical tool for the study of impact craters on the Earth and planetary surfaces by helping to determine the impact angle, direction, and composition of impactors. The