



Fig. 1.

chemistry of SNCs and each new martian sample gives us the chance for a more reliable estimate.

**Noble Gases:** Concentration and isotopic composition of noble gases have been determined in a 96-mg sample. From cosmogenic isotopes, exposure ages are calculated using the chemical composition given in Table 1 and production rates calculated according to Eugster and Michel [3] (but also including the production of  $^{21}\text{Ne}$  from Na). No shielding correction was applied. The exposure ages are in excellent agreement with those given by Eugster et al. [4] and confirm their suggestion that the exposure ages of ilmenite shergottite (~3.5 m.y.) are longer than those of basaltic shergottites (~2.5 m.y.). The K-Ar age of QUE 94201 is 1.33 G.y. Ratios for  $^3\text{He}$ ,  $^{21}\text{Ne}$ ,  $^{38}\text{Ar}$ , and  $^{40}\text{Ar}$  (in  $10^{-8} \text{ cm}^3 \text{ STP/g}$ ) are 3.57, 0.54, 0.41, and 328 respectively;  $T_3$ ,  $T_{21}$ , and  $T_{38}$  (in m.y.) are 2.2, 2.6, and 2.5 respectively.

**References:** [1] McKay S.-R. and Wagstaff J. (1996) *LPS XXVII*, 851-852. [2] Mikouchi T. et al. (1996) *LPS XXVII*, 879-880. [3] Eugster O. and Michel T. (1995) *GCA*, 59, 177-199. [4] Eugster O. et al. (1996) *LPS XXVII*, 345-346.

**RECRYSTALLIZED GLASSES AND OTHER MELTS OF THE ONAPING FORMATION AND THE ORIGIN OF THE SUDBURY IGNEOUS COMPLEX, ONTARIO, CANADA.** B. O. Dressler<sup>1</sup>, T. Weiser<sup>2</sup>, and P. Brockmeyer<sup>3,4</sup>. <sup>1</sup>Lunar and Planetary Institute, Houston TX 77058-1113, USA. <sup>2</sup>Bundesanstalt für Geowissenschaften und Rohstoffe, 30631 Hannover, Germany. <sup>3</sup>Institut für Planetologie, Universität Münster, 48149 Münster, Germany. <sup>4</sup>Present address: Heekweg 79, 48161 Münster, Germany.

The origin of the Sudbury Structure, along with associated breccias and melt bodies of the Onaping Formation (OF) and the Sudbury Igneous Complex (SIC), has been controversial. An impact origin of the 1.85-G.y.-old structure, however, has gained wide acceptance over the last decade [e.g., 1]. Nevertheless, the origin of the breccias of the OF and the SIC is still being debated. Recently the suevitic fall-back origin of the breccias of the OF has been challenged [2]. The entire SIC is either a differentiated impact melt body [1,3] or a combination of an upper granophyre impact melt and a lower, impact-triggered magmatic body consisting of quartz gabbro, norite, and the ore-bearing quartz dioritic sublayer [4].

The gray and black members of the OF contain liquid-state and solid-state recrystallized impact glass fragments that span a considerable range of chemical compositions. On the basis of our detailed microprobe work, heterogeneous, fluid-state glasses of various composition occur together with diaplectic glass fragments and target rock fragments exhibiting microscopic shock metamorphic features. Similarly, the igneous matrix of the north range basal member of the OF and the so-called melt bodies of the OF are characterized by a wide range of chemical compositions [5].

Mixing of the various glass components, the melt bodies, and the basal member should result in an impact melt with either a granophyre composition, if the SIC granophyre represents the Sudbury impact melt, or with the

bulk composition of the SIC, if the whole SIC is a differentiated impact melt sheet. In the first model, norite, quartz gabbro, and the sublayer of the SIC represent impact-triggered, endogenic magmatic rocks. We have compared our geochemical results and published data on the various glasses and melts of the OF with the compositions of the units of the SIC. On the basis of this comparison we cannot differentiate between the two above models for the origin of the SIC.

Field observations, however, appears to favor the first model, in which the granophyre alone represents the Sudbury impact melt. The SIC appears not to be one single melt sheet but is characterized by several features indicative of more than one process of formation. For example, we have observed sublayer phases intruding the norite of the SIC, contacts of the sublayer with the norite that also provide evidence of the sublayer being "younger" than the norite, and structural features strongly suggesting a prenorite formation of the granophyre [4].

Our observations and published chemical data [5] suggest that mixing of melts of the OF (i.e., glass fragments, melt bodies, and matrix of the basal member) was never complete prior to the termination of the excavation and ejection phase of the Sudbury impact process. They also support an impact model in which the granophyre, and not the whole SIC, is the Sudbury impact melt.

We are aware that our model is different from geochemical models in which the SIC as a whole is interpreted as an impact melt [3,6]. There may be other interpretations for our observations or for those of the geochemists. We hope that future work will lead to a Sudbury impact model that encompasses all field and laboratory observations.

**References:** [1] Grieve R. A. F. et al. (1991) *JGR*, 96, 22753-22764. [2] Gibbins S. F. M. (1994) M.Sc. thesis, Laurentian University, Sudbury. [3] Faggart B. E. et al. (1985) *Science*, 230, 436-439. [4] Johns G. W. and Dressler B. O. (1995) *LPS XXVI*, 679-680. [5] Muir T. L. and Peredery W. V. (1984) *Ont. Geol. Surv. Spec. Vol. 1*, 139-210. [6] Deutsch A. (1994) *GSA Spec. Paper* 293, 289-302.

**LIMITING CONDITIONS FOR SILICATE LIQUID STABILITY IN COSMIC GASES.** D. S. Ebel<sup>1</sup> and L. Grossman<sup>1,2</sup>. <sup>1</sup>Department of the Geophysical Sciences, The University of Chicago, Chicago IL 60637, USA. <sup>2</sup>Enrico Fermi Institute, The University of Chicago, Chicago IL 60637, USA.

Yoneda and Grossman [1] used the nonideal liquid solution model of [2] for the CaO-MgO-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub> (CMAS) system to calculate the stability fields of CMAS liquids; the distribution of elements between vapor, CMAS liquid, and crystalline phases; and the temperature variation of CMAS liquid compositions in cosmic gases. A liquid that crystallizes into forsterite + spinel + fassaite ± anorthite persists to total pressures ( $P^{\text{tot}}$ ) as low as  $5 \times 10^{-2}$  atm in a solar gas, and in systems with dust/gas enrichment factors relative to solar composition (DGEFs) of as little as 16 at  $P^{\text{tot}} = 1 \times 10^{-3}$  atm. Although most calculated solid-liquid equilibrium temperatures in [1] are in good agreement with those from crystal-liquid phase diagrams, the solidus temperature for this assemblage was overestimated by ~50 K, which led [1] to estimate that CMAS liquids could persist to  $P^{\text{tot}}$  as low as  $1 \times 10^{-2}$  atm in a solar gas and to DGEFs as low as 5 at  $P^{\text{tot}} = 1 \times 10^{-3}$  atm.

To delineate the stability fields in cosmic gases of liquids having chondritic compositions, we have begun to incorporate the nonideal, 15-component, regular solution model of Ghiorso and Sack [3] into condensation calculations. Their model, a computer program called MELTS, cannot be used for some SiO<sub>2</sub>-poor liquid compositions dealt with in [2] and encountered in [1], but has the advantages of being applicable to a much broader range of liquid compositions than those restricted to CMAS and, for compositions that can be handled by the models of both [2] and [3], predicting liquid-crystal equilibration temperatures more accurately than the model in [2]. Although not yet able to perform full equilibrium calculations in which the element distribution is computed between vapor, solids, and Ghiorso-Sack liquids, we can use MELTS to find the minimum DGEF necessary to generate liquid condensates at any  $P^{\text{tot}}$ . By running the condensation program of [1] at various DGEFs at each of several values of  $P^{\text{tot}}$  without allowing liquids to form, we calculated solid condensate assemblages even at conditions where liquids are more stable. For each set of conditions, we used the bulk composition of the oxide + silicate fraction of the condensate as-

semblage and the  $P^{\text{tot}}$  and  $f_{\text{O}_2}$  at each temperature step as input to MELTS to see if the condensate assemblage would have been partially molten at its calculated formation conditions. Under all conditions investigated, we found that the condensate assemblage with the lowest melting point is forsterite + fassaite + spinel. Although MELTS indicates that this assemblage would be partially molten at temperatures as low as 1480 K, experiments in Ti-bearing systems [4] suggest that liquid should not persist below 1500 K. Thus, whenever this solid assemblage was calculated to condense at  $T \geq 1500$  K, we considered it partially molten. As predicted [1],  $P^{\text{tot}}$  and DGEFs necessary to generate partially molten condensates are not as high as calculated with [2]. In a solar gas, the minimum  $P^{\text{tot}}$  is only  $\sim 5 \times 10^{-3}$  atm and, at  $P^{\text{tot}} = 1 \times 10^{-3}$  atm, the minimum DGEF is only  $\sim 3.5$ . At  $P^{\text{tot}} = 1 \times 10^{-4}$ ,  $1 \times 10^{-5}$ , and  $1 \times 10^{-6}$  atm, minimum DGEFs necessary for generating partially molten condensates are 14, 50, and 165 respectively. Partial melts may form at even lower DGEFs, as some high-temperature, low- $\text{SiO}_2$ , solid condensate assemblages with bulk compositions outside the range of applicability of [3] may condense above their minimum melting temperatures, inaccurately estimated in [2].

**References:** [1] Yoneda S. and Grossman L. (1995) *GCA*, 59, 3413–3444. [2] Berman R. G. (1983) Ph.D. thesis, UBC. [3] Ghiorso M. S. and Sack R. O. (1995) *Contrib. Mineral. Petrol.*, 119, 197–212. [4] Stolper E. (1982) *GCA*, 46, 2159–2180.

**YAMATO 791093, AN ANOMALOUS IIE IRON.** M. Ebihara<sup>1</sup>, P. Kong<sup>1</sup>, Y. Ikeda<sup>2</sup>, and H. Kojima<sup>3</sup>, <sup>1</sup>Department of Chemistry, Faculty of Science, Tokyo Metropolitan University, Hachioji, Tokyo 192-03, Japan, <sup>2</sup>Department of Earth Sciences, Faculty of Science, Ibaraki University, Bunkyo, Mito, Japan, <sup>3</sup>National Institute for Polar Research, Itabashi, Tokyo, Japan.

**Introduction:** Yamato 791093 is a small meteorite, weighing 4.12 g. Based on its petrography, this meteorite was once classified as H6 [1]. Compared with normal H chondrites, Y 791093 contains anomalously high abundances of metal and especially sulfide. This unusual petrology led us to initiate a detailed chemical and petrographical investigation on this meteorite. The aims of this study are (1) (re)classification of Y 791093 and (2) presentation of a plausible explanation for its formation.

**Experimental:** A small chip (~0.1 g) of the meteorite was cut using a wire saw and separated into metal, sulfide, and silicate portions. The silicate portion was further separated into coarse and fine fractions and the sulfide portion was separated into magnetic and nonmagnetic fractions by using a hand magnet. For the metal portion, duplicate samples (big and small pieces) were prepared. All these samples were analyzed by INAA.

**Results:** *Silicate.* Mineral compositions of the silicate portion of Y 791093 are essentially the same as those for equilibrated H chondrites (Fa<sub>17–20</sub>, Fs<sub>16–19</sub>, An<sub>11–14</sub>). In addition to these major constituent minerals, kamacite (Ni ~5.3–6.3 wt%), taenite (Ni ~55–57 wt%), and chromite are present. Besides troilite as a major sulfide, pentlandite, alabandite, and digenite were observed as accessory sulfides. In contrast to the case for silicates in (normal) IIE irons, where schreibersite is common, whitlockite was found in the Y 791093 silicate. All mineralogical and petrographic features suggest that the silicate portion of Y 791093 is an equilibrated H chondrite of petrologic type 5–6. Abundances of Mg-normalized refractory lithophiles and moderately volatile lithophiles in the Y 791093 silicate are chondritic, being similar to those for H chondrites. Both Br and Sb contents in the Y 791093 silicate are 3× and 2× higher than those in H chondrites respectively. As this meteorite seems to have experienced weathering to a considerable degree, a high abundance of Br may be due to terrestrial contamination. Magnesium content of the Y 791093 silicate is about 20% lower than the H chondrite average [2], yielding absolute abundances of the lithophiles that are systematically lower than the H chondrite values by the same factor. Nickel-normalized siderophile abundances in the Y 791093 silicate are also chondritic. Their abundances are somewhat similar to EH chondrites, possibly influenced by the surrounding metal and/or sulfide. Thus, chemical composition of the silicate portion of Y 791093 is chondritic and therefore is considerably different from that for the silicate inclusions of (normal) IIE irons [3].

*Metal.* Chemical compositions of duplicate metal samples are in good

agreement with each other, suggesting that the metal portion is homogeneous in chemical composition, and is also in agreement with those for IIE metals [4], except for Ga, which is depleted in the Y 791093 metal by a factor of 2–3. Both Ir and Cu in Y 791093 metal are located at the lower margins for their abundance ranges of (normal) IIE metal.

**Discussion:** Chemical analysis and mineralogical and petrographic observations show that the silicate portion of Y 791093 is similar to equilibrated H chondrites of either petrologic type 5 or 6. Considering that silicate is not a dominant phase and the metal composition is mostly consistent with that for IIE metal, Y 791093 may be classified as a IIE iron rather than an H chondrite. As sulfide seems to be equally or more abundant than metal, the Y 791093 meteorite may be classified as an anomalous IIE. As it is different from what is usually the case for (normal) IIE irons, the silicate portion of Y 791093 is chondritic not only in mineralogy but also chemically. From these observations, we propose the following model. The Y 791093 meteorite was formed on the surface of the H chondrite parent body. The metal-sulfide eutectic melt was caused by an impact and intruded into the H chondrite parent material, which was not affected by the impact and could preserve the H chondrite features.

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**PROPOSED BUSHVELD-VREDEFORT MULTIPLE MEGAIM-PACTS: POSSIBLE CORRELATION WITH GLOBAL 2.1–2.0-G.y. EVENTS AND THE PROTEROPHYTIC–PALEOPHYTIC BOUNDARY.** W. E. Elston, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque NM 87106, USA.

Three unique geological megafeatures, juxtaposed in South Africa (Bushveld Complex, Vredefort dome, Witwatersrand gold), may be linked to a global 2.05-G.y. catastrophe. When Cloud reclassified Precambrian time [1], he noted that the Bushveld Complex straddles the Proterophytic (prokaryotic life, anoxic sedimentation)-Paleophytic (eucaryotes, oxidized sedimentation) boundary.

The Bushveld Complex is roofless [2]. Three overlapping basins, collectively 400 km across, are outlined by inward-dipping lobes of three major units (in sequence: Rooiberg “felsite” Group; gabbroic Rustenburg Layered Suite, RLS; Lebowa Granite Suite, LGS; maximum cumulative thickness ~15 km). Most RLS and LGS spread as sills beneath Rooiberg “felsite”; local “felsite” slivers are preserved beneath or between RLS sills [3]. Interiors of Bushveld basins are obscured by LGS or post-Bushveld cover, except for 50-km areas of pre-Bushveld rocks within the two southern basins. Each consists of a pair of contrasting “fragments” in fault contact, one intensely deformed, the other relatively undeformed. RLS does not extend far into the basins [4]. Consequently, undeformed Rooiberg “felsite” rests on the pre-Bushveld Pretoria Group in undeformed “fragments.”

The Pretoria and Rooiberg Groups bracket the catastrophe. Conflicting radiometric dates either allow simultaneity [5,6] or make Vredefort younger [7]. Alternative interpretations (in order of decreasing probability) include:

1. Quasisimultaneous multiple impacts formed Bushveld and Vredefort; superheat and unprecedented deformation provided new diagnostic criteria for Bushveld-sized impacts (see #7) but destroyed classic criteria, except at Vredefort.

2. Bushveld and Vredefort resulted from unknown long-acting endogenic processes, powerful enough to simulate impact criteria at Vredefort.

3. Bushveld and Vredefort are unrelated.

The credibility of Bushveld-Vredefort multiple impacts hinges on several controversial interpretations:

1. Deformed “fragments” are wall segments of transient cavities.
2. Undeformed “fragments” slumped into transient cavities during enlargement.
3. Bushveld Complex puddled in deep (>10 km) lobate depressions, concentric with transient cavities (cf. ring synclines of planetary multiring basins) [8].

4. Rooiberg “felsite” was ejected from transient cavities. RLS erupted