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# Surface mineralogy changes induced by impact melting on ordinary chondritic parent asteroids: clues from the DaG 896 meteorite

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**Abstract.** We demonstrate that impact melting due to hypervelocity impacts significantly increases the original modal olivine (ol) versus pyroxene (px) ratio of a chondritic target rock. The ol/(ol+px) ratio for H-, L- and LL-chondrites is 39, 54 and 65% and increases to ∼ 80% in daughter impact melt rocks. Due to the expected enrichement in olivine induced by impact melting, the surfaces of ordinary chondritic parent asteroids should have reflectance spectra indicating a range of ol/(ol+px) ratios greater than the original ordinary chondritic target material.

**Key words.** asteroids, chondrites, impact melting, mineralogy, reflectance spectra

## 1. Introduction

Understanding how the mineralogies of asteroid surfaces may be altered and differ from the composition of the subsurface material is of crucial importance for the interpretation of asteroid spectra and remote sensing data (Gaffey et al. 2002). The intensely cratered surfaces of asteroids revealed by astronomical and spacecraft observations (e.g., Belton et al. 1994; Veverka et al. 1997) attest to an intense collisional history; nonetheless, little attention has been devoted to the role of impact melting in changing their surface mineralogy during their ∼ 4.55 Ga lifetime.

A key meteorite to address this issue is the Dar al Gani 896 (DaG 896) meteorite, a thoroughly studied impact melt rock from the H-chondrite parent asteroid (Folco et al. 2004). Impact melt rocks form through the total melting of target material and relatively rapid crystallization in the surface or subsurface environment of the parent impact crater (e.g., Stöffler, Keil & Scott 1991). The mineralogy of DaG 896 will be compared with that of its chondritic precursor to identify modifications produced by shock melting in the surface mineralogy of parent asteroids.

## 2. Dar al Gani 896

DaG 896 is a 22.6 g meteorite fragment found in the Dar al Gani region of the Libyan Sahara in November 2000 (Russel et al. 2003). In this section we report highlights on its classifica-

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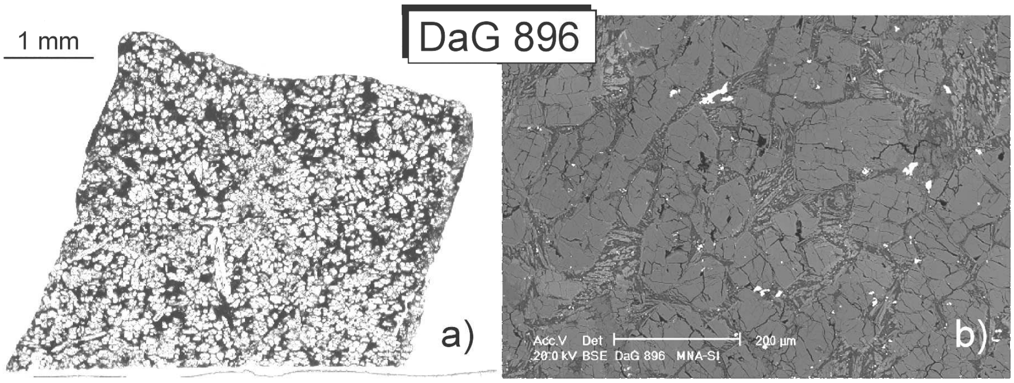


**Fig. 1.** Texture and mineral composition of DaG 896 as seen in polished thin section for optical and electron microscopy. a) Photomicrograph (transmitted light) showing the microporphyritic texture, with olivine crystals (transparent) in a dark, hyaline groundmass. b) Back Scattered Electron image showing abundant microphenocrysts of olivine (intermediate grey) set in a groundmass consisting mainly of glass (dark grey) plus quench microlites of pigeonite (pale grey).

tion and petrology, which were discussed in detail in our previous paper (Folco et al. 2004).

The DaG 896 impact melt rock has a microporphyritic texture given by abundant olivine $Fa_{17.5\pm2.1}$ ([Mn/Mg] = 0.0061) crystals with average grain-size of 100 $\mu$m, set in a groundmass consisiting mainly of Si-rich glass plus quench microlites of pigeonite $En_{59\pm5}$ $Wo_{9\pm3}$ (Fig. 1). Mineral mode (i.e., mineral abundances given in vol. %; Table 1) is olivine 69, glass 17, pyroxene 13, plus a 1% of submicrometer-sized blebs of opaque phases disseminated within glass (see also Burbine et al. 2003).

The olivine composition and the bulk oxygen isotopic composition ($\delta^{17}$O = +2.55, $\delta^{18}$O = +3.50) indicate that DaG 896 is a sample of the H-chondrite parent body. The bulk chemistry shows an H-chondritic distribution of lithophile elements, whereas chalcophile and siderophile elements are strongly depleted, indicating formation through whole-rock melting (or nearly so) of H-chondrite material, nearly complete loss of the metal plus sulphide component, and crystallization without significant igneous fractionation.

Superheated, severely shocked chondritic relics (~ 10 vol. %), typically in the form of corroded lithic fragments <100 $\mu$m in size intimately distributed within the igneous lithology, indicate disequilibrium (nearly instantaneous) melting triggered by a highly energetic impact, which possibly induced shock pressures of ~ 80 – 100 GPa. The relatively young 3.704 ± 0.035 Ga $^{40}$Ar-$^{39}$Ar crystallization age is consistent with the impact melting origin, as magmatism in the asteroid belt was active only in the first hundred million years of Solar System history.

Textural data and thermodynamic crystallization modelling suggests that DaG 896 crystallized from a liquidus temperature in excess of 1650°C under relatively slow cooling rates (~ 10°C/hr) to ~ 1300°C, before quenching. The two-stage cooling history indicates that a reasonable formation environment might be a dike intruding cooler basement below a crater floor. Metal-silicate fractionation may have been accomplished, at least at the cm-scale of the studied meteorite sample, through differential acceleration of immiscible liquids of different density during the intense flow regimes associated with the excavation and modification stages of the cratering mechanism (e.g., Melosh 1989). Alternatively, DaG 896 may represent a surface sample of a differentiated melt body at the floor of an impact crater, as gravitational settling appears to be an effective process at the surface of a chondritic parent asteroid: for metal particles 1 to 10 mm in size, typically observed in partially differentiated impact melt rocks, Stokes Law indicates a settling velocity >1 m/hr during the first few hours of crystallization on asteroidal bodies of >25 km radius. Both the above impact crater facies are thought to require the production of relatively large amounts of melt in km-sized, or larger, craters (e.g., Stöffler, Keil & Scott 1991; Gaffey & Gilbert 1998). DaG 896 is, thus, evidence for extensive impact melting on the H-chondrite parent asteroid, as Chico is for the L-chondrite parent (Bogard et al. 1995).

## 3. Modifications of the surface mineral composition

Table 1 reports mineral mode for DaG 896 and other impact melt rocks from the L and LL chondrite parent asteroids; literature data for their chondritic precursors is also reported for comparison.

Several works (Kring et al. 1996; Gaffey & Gilbert 1998; Folco et al. 2004; Grier et al. 2004) have already discussed the obvious redistribution and loss of the opaque (mostly metal) component in impact melt rocks relative to their chondritic precursors, whereas little attention has been so far given to variations in the silicate component. As such, we wish to focus here on the important modal increase in olivine relative to pyroxene observed in DaG 896 when compared to modal abundances in H-chondrites. In particular, we wish to highlight that the olivine (ol) versus pyroxene (px) ratio expressed as ol/(ol+px)*100 (Table 1) changes from 39 to 84% from H chondrites to DaG 896. We also observe a slight increase in the felsic (plagioclase + glass) component due to the modal increase in glass relative to plagioclase. The increase in olivine and glass relative to pyroxene is consistent with disequilibrium crystallization of chondritic total melts crystallizing in parent asteroid surface/subsurface environments (Stöffler, Keil & Scott 1991; Folco et al. 2004). Here cooling rates are expected to be fast enough (typically tens of °C/hr, or faster) to favour crystallization of the high-temperature phase (olivine) and quenching of residual liquids, thereby leading to the formation of glass rather than the low-temperature phases pyroxene and plagioclase.

Data for impact melt rocks from L and LL ordinary chondritic parent asteroids show the same trend described above (Table 1 and Fig. 2), although it is less pronounced. In particular, we observe that the olivine versus pyroxene ratios changes from 54 and 65% in L and LL chondrites to 73 and 81% in their daughter impact melt rocks. In conclusion, impact melt rocks of H-, L- and LL-chondritic parentage have ol/(ol+px) ranging from 73 to 84%, i.e. similar yet higher than the highest value of 65% measured in the olivine-richest LL ordinary chondrites.

## 4. Implications for spectral analysis of S-asteroids

The previous section showed how impact melting due to hypervelocity impacts increases the original modal ol/(ol+px) ratio of a chondritic target rock. An increase in the modal ol/(ol+px) ratio on the surface of an ordinary chondrite parent body will significantly affect the resulting reflectance spectrum and the resulting mineralogical interpretation.

Different minerals have distinctive absorption bands in the visible and near-infrared wavelength regions. Both olivine and pyroxene have relatively strong UV (ultraviolet) features: olivine shows a broad absorption band centered at $\sim 1\ \mu$m (Band I), whereas pyroxene tends to have two broad absorption bands centered at $\sim 1\ \mu$m (Band I) and $\sim 1.9\ \mu$m (Band II). Reflectance spectra of S-asteroids (e.g., Binzel et al. 2001) tend to have a relatively strong UV (ultraviolet) feature, a broad absorption band centered at $\sim 1\ \mu$m (Band I) and another centered at $\sim 1.9\ \mu$m (Band II). The wavelength positions and structure (width and depth) of these absorption features are characteristic of varying mixtures of olivine and pyroxene minerals (Cloutis et al. 1986). Other minerals are surely present on the surface of S-asteroids; however, these other minerals do not have diagnostic absorption features in the UV wavelength region. Some S-asteroids appear to be plausible candidates for ordinary chondrite parent asteroids (Gaffey et al. 2002).

**Table 1.** Mineral abundances (vol. %) of DaG 896 and other ordinary chondritic impact melt rocks and their precursors (data source: Dodd & Jarosevich 1976; Hoshino & Kanenori 1992; Ruzicka, Snyder & Taylor 1998; Yugami et al. 1998; Ghoshi et al. 2001; Ghoshi et al. 2002; Gastineau-Lyons, McSween & Gaffey 2002; Laridhi Ouazaa et al. 2004; Folco et al. 2004).

| | olivine | pyroxene | plagioclase + glass | metal | others | ol/(ol+px) (%) |
|---|---|---|---|---|---|---|
| DaG 896 - H impact melt | 69 | 13 | 17 | tr | tr | 84 |
| L impact melts | 60 | 22 | 22 | 1 | tr | 73 |
| LL impact melts | 61 | 14 | 23 | tr | tr | 81 |
| H chondrites | 29 | 45 | 3 | 13 | 10 | 39 |
| L chondrites | 40 | 34 | 9 | 7 | 10 | 54 |
| LL chondrites | 50 | 27 | 10 | 2 | 11 | 65 |

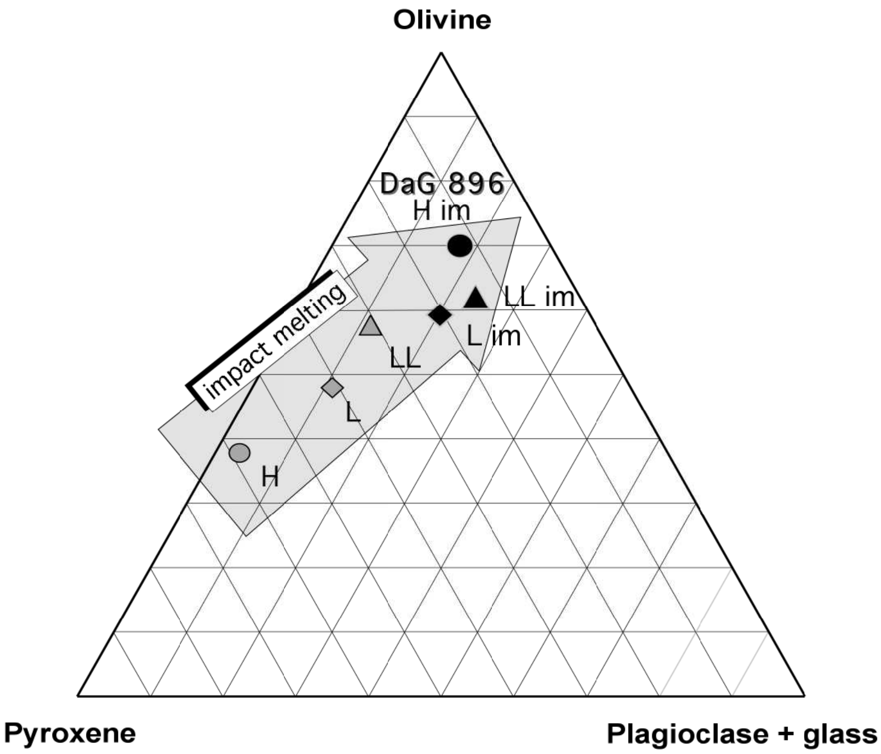


**Fig. 2.** Ternary diagram showing mineral abundances (vol%) of olivine, pyroxene and plagioclase plus glass in the DaG 896 H-chondritic impact melt rock (DaG 896 H im) relative to literature data for L and LL chondritic impact melt rocks and their chondritic precursors (Dodd & Jarosevich 1976; Hoshino & Kanenori 1992; Ruzicka, Snyder & Taylor 1998; Yugami et al. 1998; Ghoshi et al. 2001; Ghoshi et al. 2002; Gastineau-Lyons, McSween & Gaffey 2002; Laridhi Ouazaa et al. 2004; Folco et al. 2004)

The intensely cratered surface of asteroids suggests that impact melt is a plausible important addition to their surface material, although the amount of impact melt material produced during the lifetime of an asteroid is virtually impossible to quantify. Keil et al. (1997) have argued that the volume of impact melt formed on most asteroids is a small fraction of the debris generated by impacts, i.e., 0.1 to 0.01 % of the total displaced crater volume, whereas volumes orders of magnitude greater are predicted by the models by O'Keefe & Ahrens (1994). In any case, continual impacts could possibly enrich the fraction of impact melt on their surface. Furthermore, impact melt material may plausibly be added through micrometeorite impacts.

Due to the expected increase in the ol/(ol+px) ratio induced by impact melting, the surfaces of ordinary chondritic parent asteroids should have reflectance spectra indicating a range of ol/(ol+px) ratios greater than the original ordinary chondritic target material. Since we cannot quantify the amount of impact melt produced at the surface of an asteroid, it is difficult to attribute a particular olivine-rich asteroid reflectance spectrum to a given ordinary chondritic class. The mineralogy of DaG 896 (Table 1; Fig. 2) suggests that an S-asteroid with spectrally inferred ol/(ol+px) ratio similar to LL-chondrites could actually be an H-chondrite parent body enriched in impact melt material at its surface.

The Hayabusa sample return mission to near-Earth asteroid 25143 Itokawa will provide an opportunity to test the hypothesis of olivine enrichment on the surface of asteroids due to impact melting (Burbine & Folco 2005). Itokawa has a reflectance spectrum similar to that of LL chondrites (Binzel et al. 2001). If olivine enrichment is occurring on the surface of Itokawa and Itokawa is composed of ordinary chondritic material, we expect the samples returned from Itokawa to have an olivine composition and bulk oxygen isotopic composition similar to that of H or L chondrites.

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