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ORIGIN OF UNUSUAL IMPACT MELT ROCKS, YAMATO-790964 AND -790143 (LL-CHONDRITES)

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Abstract: We have studied Yamato (Y)-790964 and -790143, which are unusual paired impact-melted LL chondrites. Some petrologic aspects of these impact melt rocks are similar to those of the impact melted L-chondrite, Ramsdorf; these meteorites experienced nearly total melting, yet partly preserve chondritic textures. Olivine and chromite grains in Y-790964 and olivine in Y-790143 are the only relicts of the precursor materials; they were solid clasts during impact melting. All other portions (*i.e.*, chondrules and matrices) were totally melted. It appears that the chondrule ghosts, which are mainly composed of very fine-grained igneous-textured pyroxene, minor olivine and other phases, were melted and crystallized *in situ*, without significant mixing with less viscous melts. Partial resorption of olivines and chromites suggests that the post-shock temperature could be >~1600°C. The minor local differences in mineralogy appear to be consistent with small spatial variations in thermal history. Evidence of complex injection of troilite, Fe,Ni-metal and feldspathic glass into the relict minerals suggests that the precursor rock was shocked *in situ*. The shock pressure might have been >75 or 90 GPa for a non-porous precursor rock or >20–40 GPa for a porous rock.

1. Introduction

Yamato (Y)-790964 and -790143 are grouped with other impact melted Yamato-LL chondrites which are thought to belong to a single meteorite shower (MIYAMOTO *et al.*, 1984; OKANO *et al.*, 1990). NAKAMURA and OKANO (1985) and OKANO *et al.* (1990) reported shock ages of these meteorites of ~1.2 Ga. The textures and mineralogies of these impact melt rocks are enigmatic. Although these rocks contain possible fragments of the precursor materials, the clast-matrix texture is not clear. In addition, they contain abundant chondrule ghosts of unknown origin. Except for Ramsdorf (BEGEMANN and WLOTZKA, 1969; YAMAGUCHI *et al.*, 1996a,b), such characteristics have not been observed in other impact-melted ordinary chondrites (*e.g.*, SCOTT *et al.*, 1986a,b; BOGARD *et al.*, 1995). A number of petrologic studies of Y-790964 and -790143 have already been performed (MIYAMOTO *et al.*, 1984; OKANO *et al.*, 1990; YANAI *et al.*, 1981), but a detailed study of the complicated textures formed by shock and impact melting is still lacking. This paper reports such a study. We also compared these unusual impact melt rocks to

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other impact melts, in the light of recent studies of impact melted meteorites (*e.g.*, Stöffler *et al.*, 1991; Scott *et al.*, 1997) to elucidate impact melting processes on asteroids. A preliminary study was given by Yamaguchi *et al.* (1996b).

2. Samples and Analytical Techniques

Optical microscopy was performed with a Nikon petrographic photo-microscope equipped for transmitted and reflected light. We observed microtextures using a Zeiss DSM 962 scanning electron microscope (SEM). Minerals were analyzed with a Cameca Camebax electron probe microanalyzer (EPMA) operated at an accelerating voltage of 15 keV and beam current of 20 nA for olivine, pyroxene and chromite, and 10 nA for mesostasis glasses. Natural and synthetic phases of well-known compositions were used as standards, and data were corrected using a ZAF program.

3. Results

Y-790964 and -790143 are very heterogeneous impact melt rocks, containing abundant vugs (Okano *et al.*, 1990; Miyamoto *et al.*, 1984) (Fig. 1a). These rocks consist of large (<1.5×0.6 mm), angular to irregular relict olivines, irregular to rounded chondrule ghosts, set in a very heterogeneous igneous matrix (Okano *et al.*, 1990). We have defined the following textural units: relict minerals (olivine and chromite), fine-grained pyroxene and/or olivine, barred olivine and olivine-pyroxene chondrule ghosts, and impact melt matrix.

3.1. Relict minerals (olivine and chromite)

Relict olivines are irregularly shaped and up to several mm in size. They are characterized by dusty features due to the presence of tiny (<1–2 μm) opaque phases (troilite and FeNi-metal) which are mainly located along healed cracks and fractures (Figs. 1b, 2a,b). The relict olivines show weak to strong undulatory extinction and week mosaicism, but we rarely observed recrystallization textures, suggesting that the shock stage of these crystals range from S2 to S3 (Stöffler *et al.*, 1991). These relict olivines are partly replaced by granular crystals (10–50 μm in size) with interstitial feldspathic glass. The olivine granules grew from the edge of the relict olivines (Figs. 2a,b). These textures are in some cases difficult to distinguish from a recrystallization texture, but the euhedral shape of some olivines and the presence of interstitial glass clearly indicates an igneous origin. In some cases, irregular FeNi-FeS grains (~100 μm) are interstitially located in fractures in the relict olivines, closely associated with feldspathic glass and minor euhedral pyroxene. The presence of veins of opaques and feldspathic glass suggests that these olivines were not melted during the impact event, in contrast to pyroxene grains (see below).

Another phase in Y-790964 that was not completely melted by the impact event is

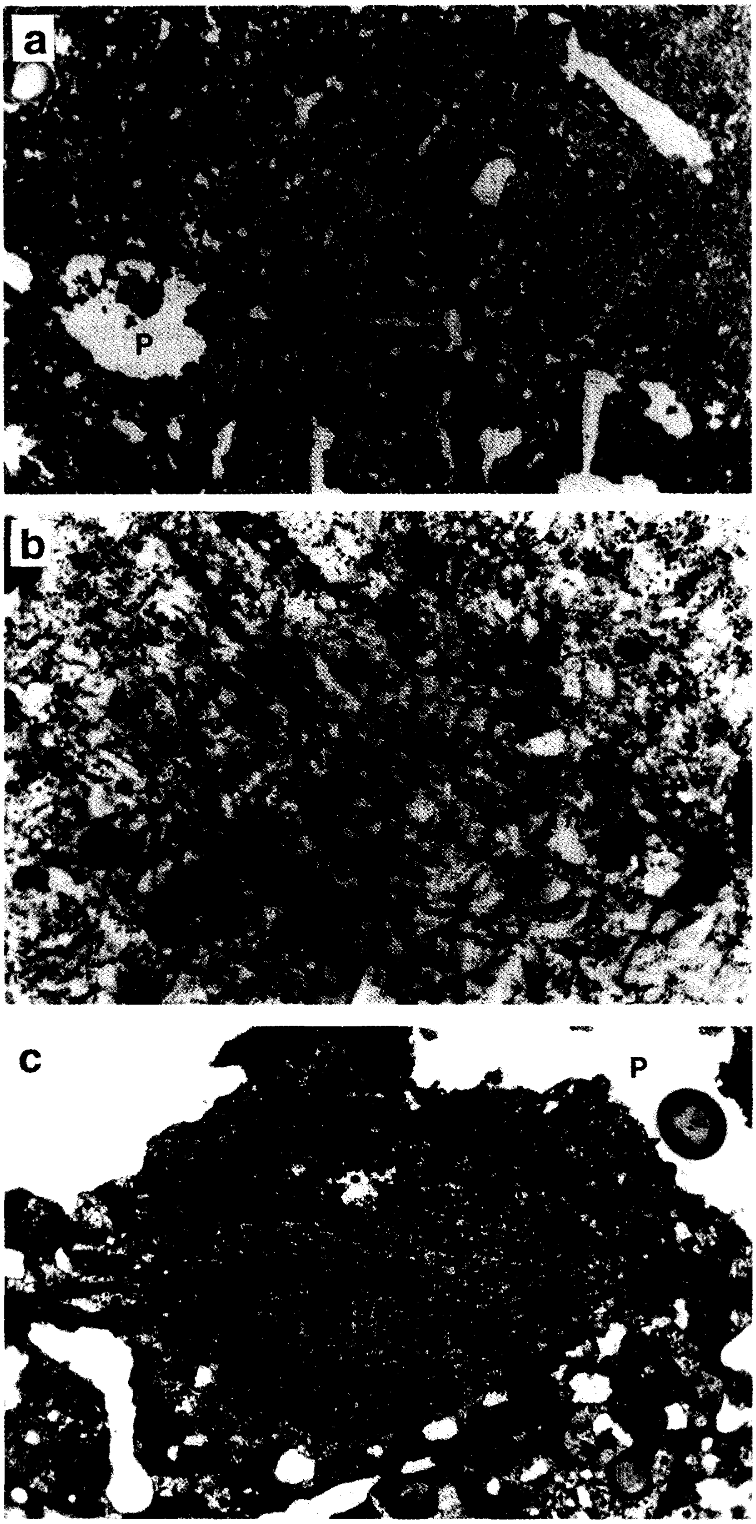

Fig. 1. Photomicrographs in transmitted, plane polarized light of (a) overall view of Y-790964, showing a heterogeneous texture with abundant vesicles, (b) olivine relict, showing a dusty appearance due to the presence of tiny inclusions of Fe-metal and troilite and (c) fine-grained pyroxene chondrule ghost. Planes of fields of (a), (b) and (c) are 5.6, 0.6 and 2.6 mm, respectively. P: pore spaces.

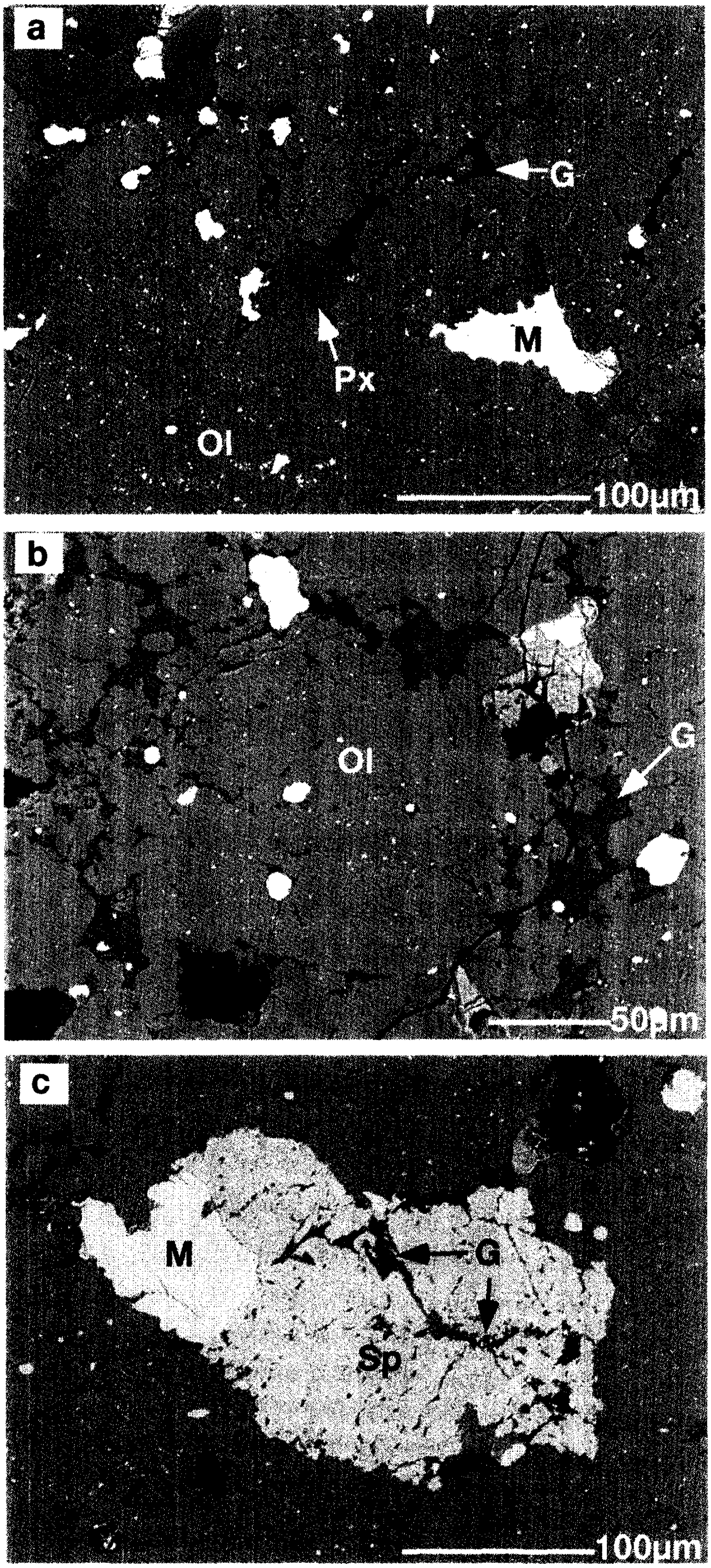

Fig. 2. Back-scattered electron images (BEIs) of relict minerals. (a) The core of a large relict olivine (Ol), invaded by feldspathic melt (G) and opaque minerals (Fe-metal and troilite) (M). Note the presence of euhedral olivines and pyroxenes along fractures. (b) Relict olivine (Ol) in impact melt matrix, surrounded by overgrowth of fine euhedral olivines. (c) Chromite relict (Sp) with complex intrusion of feldspathic glass (G), surrounded by fine-grained igneous crystals. Light gray: pyroxene; dark gray: feldspathic glass (mesostasis); white: opaques.

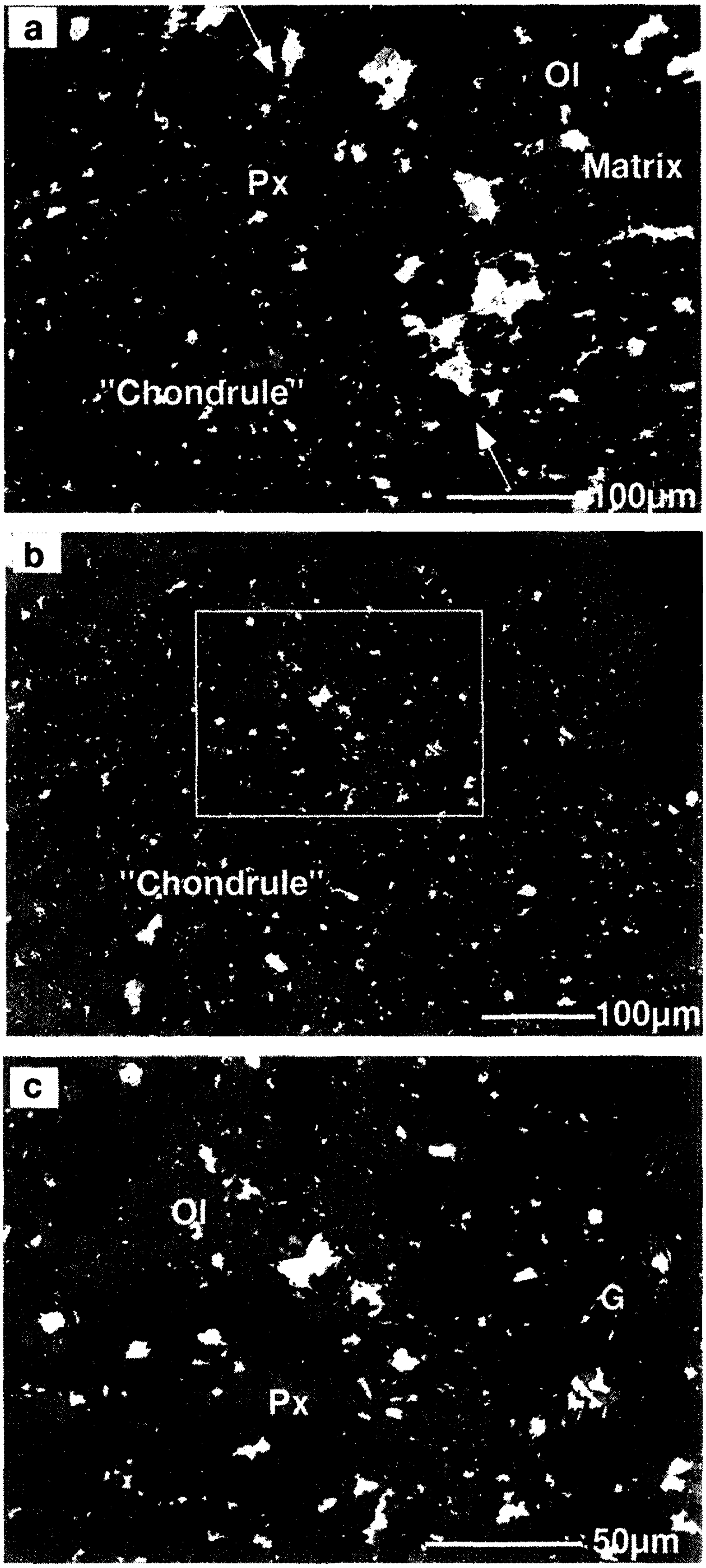

Fig. 3. BEIs of chondrule ghosts. (a) and (b) Fine-grained pyroxene-rich chondrule ghosts. There is no well-defined boundary with the matrix. The boundary is solely defined by the distribution of opaques, changes in grain size and other subtle textural changes (indicated by arrows). In some chondrule ghosts, fine-grained igneous olivines in the matrix extend inside the chondrule ghosts. (c) Enlarged view of the interior of the chondrule ghosts (b). Light gray: olivine; medium gray: pyroxene; dark gray: feldspathic glass; white: opaques.

chromite (Fig. 2c). Chromite grains (50–150 μm) are irregularly shaped and contain inclusions and veins of feldspathic glass and troilite-metal, mainly filling cracks. Some of the veins have fine (<1 μm) overgrowth of igneous chromites along the veins and the boundaries toward feldspathic glass or impact melt portion (Fig. 2c). This is texturally similar to the olivine relicts, suggesting that the chromite grains are also relicts of the precursor rocks. However, chromites in Y-790143 show euhedral morphology (<50 μm), suggesting that they were melted.

3.2. Fine-grained pyroxene-olivine chondrule ghosts

Fine-grained pyroxene-rich chondrule ghosts are rounded to irregular in shape and often do not have clear boundaries (Fig. 3). At high magnification, the boundaries are defined by a gradational change in crystal sizes, abundances of minerals, and presence of relict olivines. In Y-790143, a few pyroxene-rich chondrule ghosts have well-delineated boundaries. Many opaque minerals are roughly located along the rim of the chondrule ghosts (Fig. 3a). In some chondrule ghosts, aggregates of fine-grained euhedral olivine in the chondrule ghost extend into the igneous matrix (Figs. 3b, c). Fine-grained pyroxene chondrule ghosts are similar to radial pyroxene chondrules (LUX *et al.*, 1981), which are primarily composed of fine-grained (<10–30 μm in diameter), lathy to granular pyroxenes with minor olivine crystals (5–10 μm), opaque minerals, and interstitial mesostasis. The boundaries do not look like those formed by mechanical mixing but show igneous textures. These textural features are very similar to those of chondrule ghosts in Ramsdorf (YAMAGUCHI *et al.*, 1996a,b), which often contain small vesicles as in the barred olivine types (see above). Pyroxene grains in this type contain well-developed polysynthetic twinning (STÖFFLER *et al.*, 1991).

3.3. Barred olivine and olivine-pyroxene chondrule ghosts

We found a few barred olivine-pyroxene chondrule ghosts (Fig. 4); some of them are texturally similar to fine-grained pyroxene-olivine chondrule types (see above). Each olivine bar is ~20 μm in width and is composed of fine granules ~20 μm in size. Individual olivine crystals in the bars show similar crystallographic orientation. Pyroxenes and minor opaques fill interstices of olivine grains. As in the matrix pyroxene, pyroxenes in these types are polysynthetic twined (STÖFFLER *et al.*, 1991). Olivine grains in finer bars contain opaque dust, in contrast to the interstitial pyroxenes which are very clear. It is not clear whether this dust locates subgrain boundaries of the olivine grains or not (Fig. 4).

3.4. Matrix

The impact melt matrix tends to show microporphyritic texture but with a complex mixture of various sizes of pyroxene, relict olivines, glassy to microcrystalline mesostasis, and opaque phases (Fig. 5). Modal abundances and crystal sizes vary widely on a scale of hundreds of μm from pyroxene-rich (possibly part of pyroxene-rich chondrule ghosts) to olivine-rich. One olivine portion mostly consists of fine euhedral olivine (<10–20 μm) with interstitial mesostasis. Matrix minerals in Y-790143 are slightly smaller than those in Y-790964. Euhedral igneous olivines are generally tiny, less than 20–50 μm.

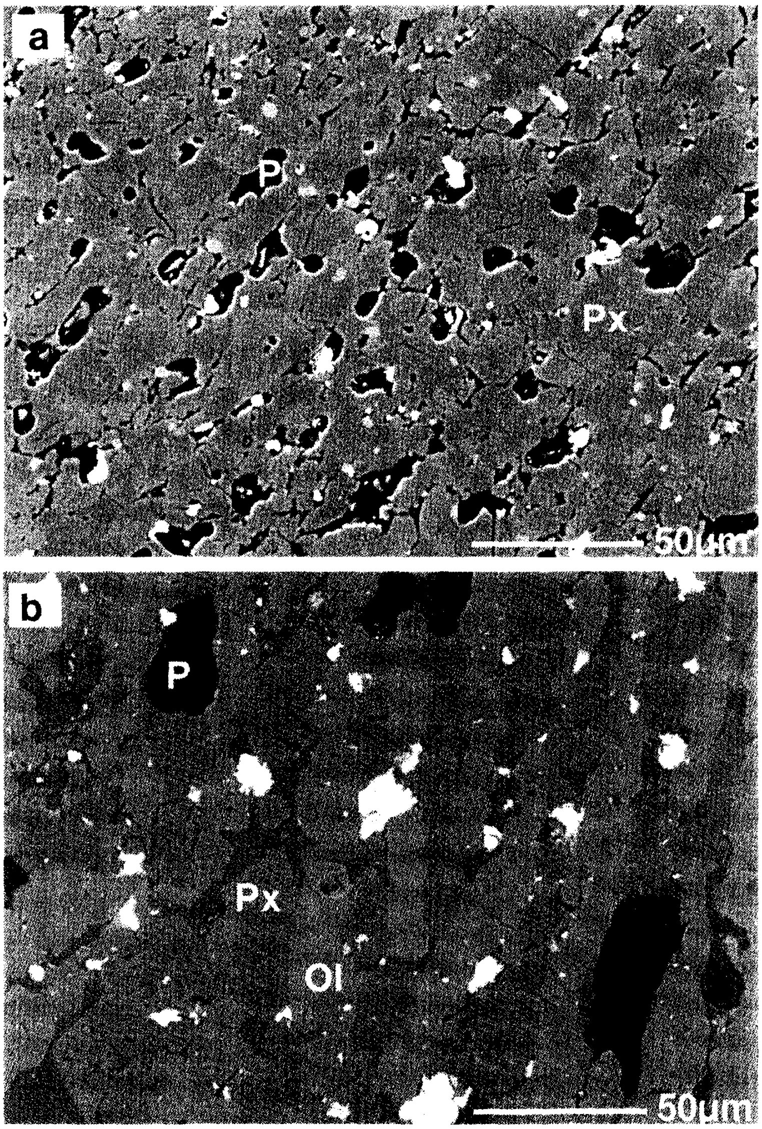

Fig. 4. BEIs of (a) barred pyroxene chondrule ghost and (b) olivine-pyroxene chondrule ghost. These chondrule ghosts are slightly vesiculated. Light gray (Ol): olivine; medium gray (Px): pyroxene; dark gray: feldspathic glass (mesostasis); black (P): pore space.

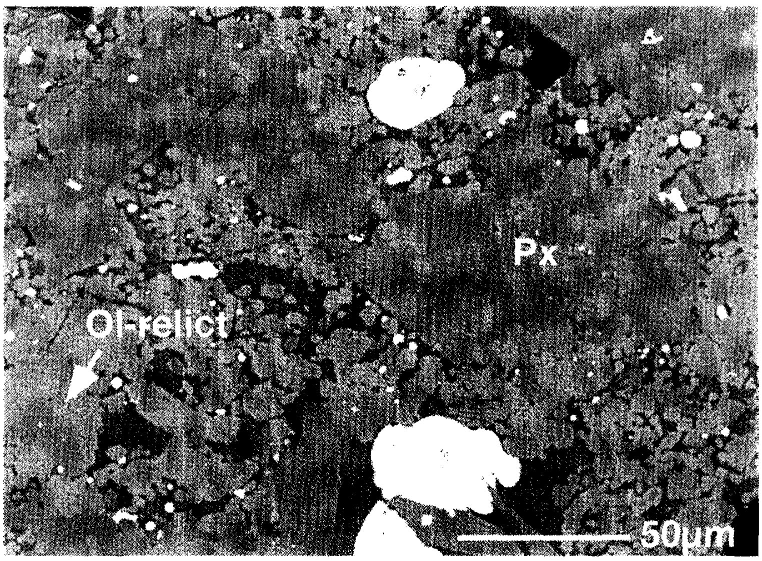

Fig. 5. BEI of matrix in Y-790143, composed of various sizes of pyroxene laths and very fine-grained igneous olivine. A relatively large olivine relict can be seen on the lower left. Light gray: olivine; medium gray: pyroxene; dark gray: feldspathic glass; white: opaques.

Sizes of euhedral pyroxene laths vary from 30x70 μm to 700x80 μm in size. Large pyroxene laths are generally clear and show weak mottled extinction. Some of them contain polysynthetic twinning (STÖFFLER *et al.*, 1991). Most of the pyroxene grains in the matrix in Y-790143 are finer than those in Y-790964 (<~20–50 μm). Large igneous pyroxenes often contain chadacrysts of olivines (~10 μm in size) in the core portions. Mesostasis is glassy to microcrystalline. Troilite is generally interstitially located between the silicate minerals, which also commonly contain fine droplets of FeNi-metal (a few μm to several tens μm in size).

3.5. Mineral compositions

Pyroxenes in both Y-790964 and -790143 are widely zoned from about Wo_2En_{72} to $Wo_{33}En_{51}$ (Fig. 6, Table 1). The compositional variations among different lithologies are similar to one another in our sections and are also similar to those shown by MIYAMOTO *et al.* (1984) and OKANO *et al.* (1990). Ca-rich pyroxenes (augites) are rarely observed in chondrule-ghosts. The Wo contents of pyroxenes in pyroxene chondrule ghosts are significantly higher than those in ordinary chondrites (SCOTT, 1984). Minor elements in pyroxenes such as Al_2O_3 (0.19–1.31 wt%), TiO_2 (0.00–0.30 wt%), Cr_2O_3 (0.47–1.47 wt%) are also slightly zoned.

Compositions of olivines are shown in Fig. 7 and Table 2. Olivine in these rocks are enriched in CaO up to 0.37 wt%, which is unusually high compared to those even in type 3 ordinary chondrites (SCOTT, 1984). The euhedral igneous olivines also show diverse CaO contents, but they are slightly lower than those of the relict olivines. This is similar to the chemical trends observed in Ramsdorf (YAMAGUCHI *et al.*, 1996a,b), although the explanation is not clear in these rocks. Fa contents in most olivines are roughly consistent with those in LL-chondrites (GOMES and KEIL, 1980). Enrichment in Fa contents in olivines (OKANO *et al.*, 1990) compared to those of matrix is not clear. Olivines in a fine-grained pyroxene-olivine chondrule shows a wide range of Fa contents (27.7–38.1), which are much higher than the range of equilibrated LL-chondrites. No

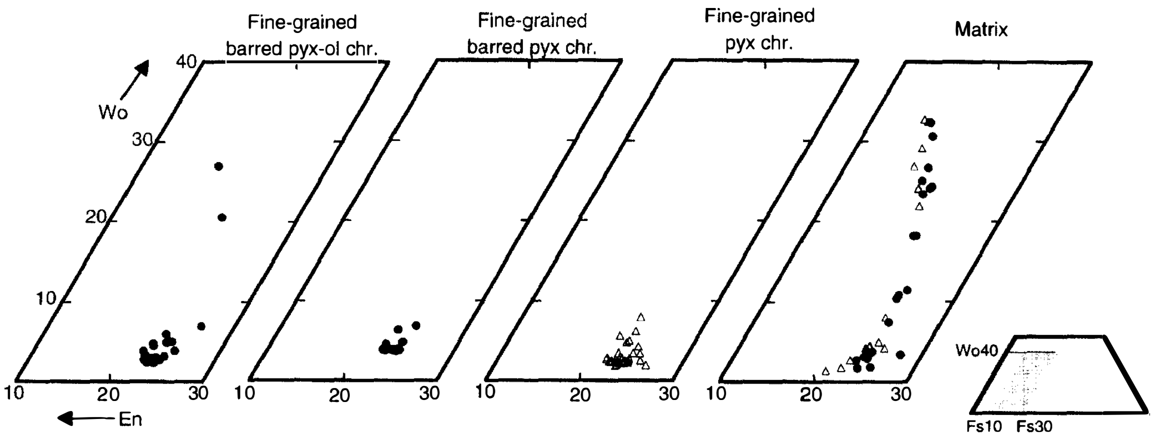

Fig. 6. Portions of pyroxene quadrilaterals for various lithologies in Y-790964 (solid circles) and -790143 (open triangles). The broad similarities of the zoning trends suggest that all pyroxenes crystallized from melts in the same impact event. Differences in the degree of Ca zoning may reflect various factors such as timing of crystallization and density of nuclei.

Table 1. Chemical compositions (wt%) of pyroxenes in Y-790964 and -790143.

	Y-790964						Y-790143			
	pyx chr.*		barred ol-pyx		matrix		pxy chr.*		matrix	
	1	2	1	2	1	2	1	2	1	2
SiO_2	55.1	55.3	55.2	53.1	53.6	53.9	55.9	55.0	55.4	53.8
Al_2O_3	0.16	1.22	0.29	0.82	0.19	1.31	0.16	0.48	0.24	0.93
TiO_2	0.15	nd	0.09	0.12	0.00	0.30	0.05	0.15	0.06	0.21
FeO	16.2	14.9	15.4	16.3	16.4	10.2	14.5	14.5	14.7	12.8
MnO	0.40	0.32	0.40	0.41	0.39	0.36	0.38	0.42	0.38	0.37
MgO	26.9	25.2	26.6	23.2	26.8	17.7	27.7	25.0	27.4	20.1
CaO	0.82	2.06	1.37	3.38	0.98	15.7	1.36	4.09	1.44	10.8
Cr_2O_3	0.10	0.34	0.64	0.75	0.47	1.47	0.60	0.86	0.84	1.31
Total	99.8	99.4	100.0	98.1	98.8	100.9	100.7	100.5	100.4	100.3
Wo	1.61	4.23	2.72	6.98	1.92	32.58	2.65	8.15	2.82	22.13
Fs	24.90	23.84	23.85	26.24	25.11	16.43	22.06	22.52	22.47	20.41

*Pyroxene-rich chondrule ghost.

systematic variation in minor elements in olivines was observed.

Chromite compositions in Y-790964 and -790143 are significantly different (averages of $Usp_{11.4}Cm_{71.7}$ for Y-790964 and $Usp_{3.8}Cm_{82.6}$ for Y-790143, Fig. 8, Table 3). Chromite grains in Y-790964 are mainly relicts, complexly replaced by other phases (Fig. 2), but those in Y-790143 are smaller and euhedral in shape, suggesting an igneous origin.

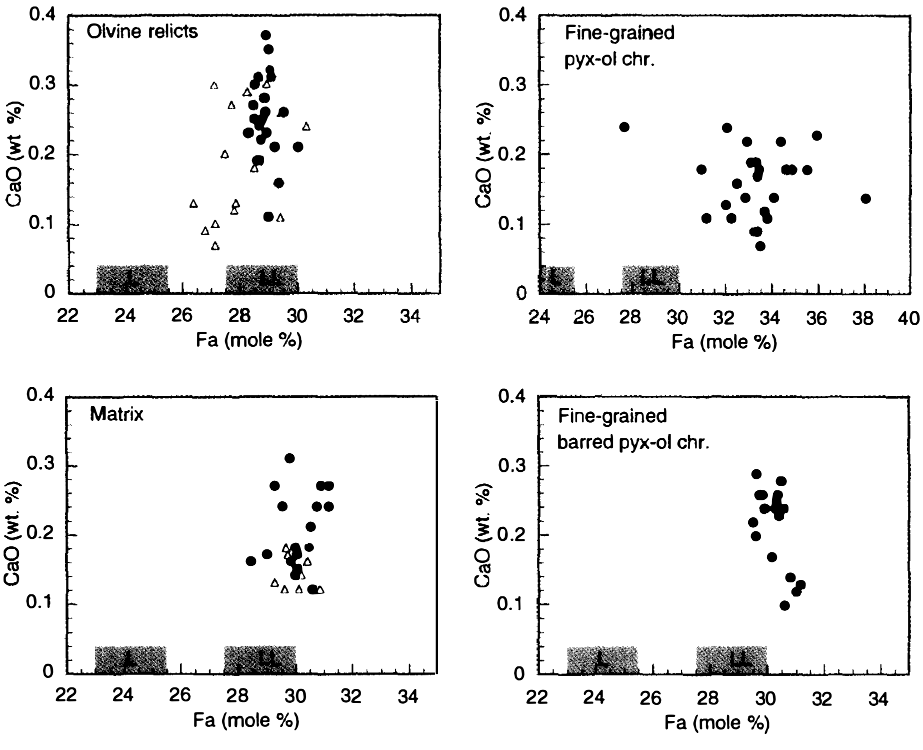

Fig. 7. Olivine compositions of various lithologies in Y-790964 (solid circles) and -790143 (open triangles).

Table 2. Chemical compositions (wt%) of olivines in Y-790964 and -790143.

	Y-790964				Y-790143		
	relict1 (20)	relict2 (5)	barred ol-px (4)	euhedral (25)	relict1 (7)	relict2 (7)	euhedral (8)
SiO_2	37.4	37.1	37.8	36.6	36.9	38.2	37.9
Al_2O_3	0.01	0.06	0.00	0.01	0.08	0.06	0.09
TiO_2	0.00	0.07	0.06	0.02	0.04	nd	0.08
FeO	26.0	26.2	27.2	29.5	26.7	25.6	26.9
MnO	0.39	0.44	0.45	0.43	0.46	0.40	0.44
MgO	35.8	34.6	34.5	32.9	35.6	36.6	35.1
CaO	0.26	0.32	0.17	0.16	0.16	0.18	0.14
Cr_2O_3	0.27	0.73	0.15	0.14	0.85	0.42	0.17
Total	100.0	99.6	100.4	99.7	100.8	101.5	100.9
Fa	28.84	29.72	29.93	33.35	29.57	28.11	29.99

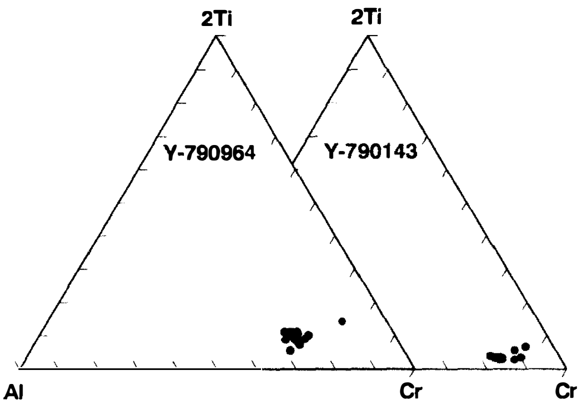

Fig. 8. Chromite compositions in Y-790964 and -790143, showing significant compositional variation. Chromites in Y-790964 are relicts and those in Y-790143 are igneous in origin.

Table 3. Chemical compositions (wt%) of spinels in Y-790964 and -790143.

	Y-790964		Y-790143	
	sp1	sp2	sp1	sp2
SiO_2	0.05	0.04	0.11	0.10
Al_2O_3	6.07	5.58	7.57	4.94
TiO_2	3.70	4.75	1.13	2.07
FeO	27.8	26.9	24.5	25.8
MnO	0.39	0.31	0.32	0.30
MgO	5.37	5.97	6.62	5.75
CaO	0.01	0.02	0.09	0.08
Cr_2O_3	54.9	55.2	58.6	59.5
V_2O_5	0.90	0.76	0.70	0.69
Total	99.2	99.5	99.7	99.2
Usp	9.91	12.46	2.99	5.58
Cm	74.49	71.56	81.34	84.03

4. Discussion

The LL chondrite impact melt rocks that include Y-790964 and -790143 are very unusual in their textures and mineral compositions (MIYAMOTO *et al.*, 1984; OKANO *et al.*, 1990). YAMAGUCHI *et al.* (1996a,b) have shown that the impact melt portions of Ramsdorf are texturally similar to Y-790964 and -790143 except for the presence of abundant vugs in Y-790964 and -790143 . However, they are texturally different from any other impact melt rock (*e.g.*, STÖFFLER *et al.*, 1991; BOGARD *et al.*, 1995).

Crystallization temperatures of minerals of Y-790964 were estimated by a program "MELTS" (GHIORSO and SACK, 1994), using the bulk composition of Y-790964 (YANAI and KOJIMA, 1995) with oxygen fugacity of IW buffer. Under equilibrium conditions, the liqudus temperature of this rock is ~1620°C, the temperature at which olivine starts crystallizing, and spinel appears at ~1470°C and pyroxene at ~1230°C. In contrast, the solidus temperature of olivine (Fa_{30}) is ~1600°C (BOWEN and SCHAIRER, 1932), that of pyroxene (Fs_{25}) is ~1400–1450°C (HUEBNER and TURNOCK, 1980), and that of chromite is ~1635°C (LEVIN *et al.*, 1969).

The presence in olivine and chromite of injected feldspathic melts and Fe-metal and troilite (Fig. 2) suggests that they are relict solids that survived the impact event. Metal-troilite injections into silicate minerals due to shock are commonly observed in shocked ordinary chondrites causing "shock darkening" (*e.g.*, RUBIN 1992; STÖFFLER *et al.*, 1991). Formation of feldspathic glass requires pressures of at least 30 GPa and mobilization of feldspathic melts may require >45–55 GPa (STÖFFLER *et al.*, 1991). However, olivine relicts show little mosaicism, suggesting that shock pressures may have been lower than 30–35 GPa (STÖFFLER *et al.*, 1991) or the mosaicism may have been removed by annealing (BAUER, 1979). If the precursor was porous, extensive melting would have occurred at 30–35 GPa (STÖFFLER *et al.*, 1988). Recrystallized olivines are rare in Y-790964 and -790143, in contrast to Ramsdorf which contains abundant recrystallized olivines. This suggests that Y-790964 and -790143 olivines were less heated than Ramsdorf olivines (YAMAGUCHI *et al.*, 1996a,b). This is consistent with the fact that Ramsdorf does not contain any relict chromites (YAMAGUCHI *et al.*, 1996a,b). Although there is no evidence that high pressure phases formed in Y-790964 and -790143, we cannot exclude the possibility that the recrystallized olivines or other minerals may have formed from such phases. However, high pressure phases have only been found in meteorites in or adjacent narrow melt veins (*e.g.*, CHEN *et al.*, 1996) that would have been quenched by the adjacent cool rock. In Y-790964 and -790143, the melts probably cooled much more slowly as the Fe concentrations in relict olivines have been partially equilibrated.

The origin of the fine-grained pyroxene chondrules is problematic. OKANO *et al.* (1990) suggested that they are unmelted precursor materials. However, we argue that pyroxenes in the chondrule ghosts crystallized from melts during the impact event. First, fine-grained chondrule ghosts are often vesiculated (Fig. 4) as in the matrix, suggesting that they were melted during the impact event. Second, compositional zoning trends in pyroxenes are broadly similar in chondrule ghosts and matrices and different from those in normal chondrites (JONES, 1996), suggesting similar crystallization histories (Fig. 6). Third, the absence of sharp boundaries between chondrule ghosts and matrix suggests that they are likely to have crystallized from the melt. Fourth, as discussed above, crystallization temperature of pyroxene (~1230–1450°C) of this rock is significantly lower than those in olivine (~1620°C) and chromite (~1470–1635°C) which partly melted. Fifth, pyroxene-rich melts would be much more viscous (~20 Pa s at 1500°C) than the matrix melts (~7 Pa s at 1500°C) according to SHAW's (1972) method. We suggested that the enhanced viscosity of Si-rich melts helped to prevent mixing with surrounding melts. Finally, the irregular shapes of chondrule ghosts are easy to understand if we assume that the chondrules were totally molten, because of the absence of fracturing and other definitive deformation features in pyroxenes. Therefore, it is likely that the pyroxenes in Y-790964 and -790143 were totally melted during the impact event.

As discussed for Ramsdorf (YAMAGUCHI *et al.*, 1996a,b), the relative enrichment (or variations) of Fa in olivine in contrast to those in the matrix can be explained by various degrees of equilibration during impact melting (OKANO *et al.*, 1990). However, enrichment of Ca in the relict olivine as compared to the matrix olivine which has also been reported in case of the impact melt rock Ramsdorf (YAMAGUCHI *et al.*, 1996a) cannot be easily explained. Both shock-melted Y-79 LL-chondrites and Ramsdorf share similar properties such as thermal histories with high peak temperatures and rapid cooling and unique impact melt textures, except for the fact that Y-79 impact melts have abundant vesicles. As suggested by OKANO *et al.* (1990), this Ca-enrichment cannot be due to the high temperature equilibration, since the distribution coefficient of Ca between melt and olivine is as low as 0.01 (*e.g.*, COLSON *et al.*, 1988). In other words, if olivine crystals are equilibrated with either mesostasis or whole rock melt, the Kd must be at least >0.3. It can be easily concluded that the precursor olivines in both meteorites were rich in Ca (OKANO *et al.*, 1990). However, SCOTT (1984) suggested that such enrichment of Ca >0.3 wt% is extremely rare even in the type-3 ordinary chondrites. Ca enrichments of olivine were ubiquitously observed in various types of relict chondrule ghosts. We suspect that this may be due to enhancement of Kd at high temperature (>1400–1500°C; see below).

The bulk composition of Y-790964 (YANAI and KOJIMA, 1995) is within the range of the average bulk of 13 LL-chondrites (JAROSEWICH, 1990). This suggests that despite the presence of the vesicles, FeS and other volatiles were not lost, in contrast to Ramsdorf. The minor local differences in chemistry (OKANO *et al.*, 1990) and mineralogy (Figs. 7, 8) appear to be consistent with small spatial variations in the thermal histories, as observed in Ramsdorf (YAMAGUCHI *et al.*, 1996a), despite almost total *in situ* melting. These variations are trivial in comparison with those observed in other impact melted chondrites like Chico which contain well-defined chondritc clasts mixed with impact melt (BOGARD *et al.*, 1995).

Y-790964 and -790143 were formed by shock melting of LL-chondrites on an asteroid ~1.2 Ga ago (OKANO *et al.*, 1990). The almost total melting of this rock suggests that the shock pressure was >75–90 GPa for a non-porous precursor rock and >20–40 GPa if the precursor was porous (STÖFFLER *et al.*, 1988, 1991). CHEN *et al.* (1996) suggested that the pressure estimates like those of STÖFFLER *et al.* (1988, 1991) are too high because they conclude that ringwoodite and other high pressure phases, which crystallized in an S6 chondrite in the pressure range 20–24 GPa, did not crystallize during pressure release. However, LINGEMANN and STÖFFLER (1994) argued to the contrary. Nevertheless, pressure estimates must be made with caution because there are many other critical factors including the duration of the shock event (CHEN *et al.*, 1996; SHARP *et al.*, 1997). The inferred high shock pressure suggests that these rocks were located near the center of the impact crater. Rapid cooling rates of these rocks suggest that they were excavated from the crater as a small object less than several tens of cm in size. This material must have reaccreted on the same or a separate sizable body to survive for ~1.2 Ga.

5. Conclusion

We conclude that impact melt rocks Y-790964 and -790143 experienced almost total *in situ* melting by shock. The only relicts observed are olivine and chromite grains, suggesting the post-shock temperature of these rock was at least above the solidus temperature of pyroxene of ~1230–1450°C and perhaps close to the liquidus temperature of these rocks of ~1620°C. According to the classification of STÖFFLER *et al.* (1991), along with Ramsdorf (YAMAGUCHI *et al.*, 1996a,b), impact melt rocks of Yamato LL-chondrite could be the highest preserved shocked material; the shock pressure could have been ~75–90 GPa (>20–40 GPa if porous) and the post-shock temperature could have been ~1500–1750°C, or higher (STÖFFLER *et al.*, 1988, 1991). This suggests that the precursors were possibly located near the center of crater where the highest shock pressures are reached (STÖFFLER *et al.*, 1991). The presence of such impact melts suggests that the LL-chondrite parent bodies may have experienced a collisional history like that proposed for the L-chondrite parent body (HAACK *et al.*, 1996).

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