

Basalts in the Lancé Carbonaceous Chondrite

Gero Kurat and Alfred Kracher

Naturhistorisches Museum, A-1014 Vienna, Austria

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Dedicated to Prof. Dr. H. Hintenberger on the occasion of his 70th birthday

We describe three lithic fragments from the Lancé carbonaceous chondrite which apparently are of igneous origin and of basaltic parentage. They consist of large enstatite grains (phenocrysts?) which poikilitically include some olivine and abundant Fe-Ni metal and Fe sulfide blebs. These enstatites are set into a matrix of partly ophitic and partly porphyritic plagioclase (\sim an71) and interstitial clinopyroxene and clinopyroxene plus plagioclase intergrowths. Mineral compositions are highly variable and reflect a complex genesis. Olivine compositions range from fo5 to fo60 and sometimes exhibit compositional zoning. Enstatites are mostly of en98 composition with some Fe-enrichment towards grain surfaces and cracks. Plagioclases have about an71 but mostly are altered to nonstoichiometric high-alkali compositions (with original Al/Si ratios corresponding to \sim an70) or are partly replaced by K-free nepheline. Generally two clinopyroxenes are present within the plagiophytic portions of the fragments: One low Fe/Mg augite (\sim en53 wo44) rich in Ti, Al, Cr, and Mn ($\text{Fe/Mn} \leq 2$) and a ferrosalite (\sim en15 wo47) poor in Ti, Cr, and Mn ($\text{Fe/Mn} \sim 100$). One fragment also contains spinel (hercynite) which apparently is xenocrystic in nature.

Our investigation indicates: (1) The fragments are of igneous origin. (2) The original melt was of basaltic composition, crystallizing the primary mineral association ol + en + plag + low-Fe augite. (3) During crystallization the melt suffered strong reduction which led to segregation of Fe-Ni droplets from the melt and which continuously lowered the Fe/Mn ratio of successively crystallizing silicates from nearly chondritic (~ 100) to 0.6. (4) Probably after incorporation into the Lancé breccia the fragments suffered to different degrees metasomatic alterations which were caused by the addition of Na, K, and Fe to the system.

The origin of the pre-Lancé basaltic melt cannot yet be established.

Introduction

Basaltic lithic fragments from within a chondrite have first been briefly described by us from the carbonaceous chondrite Lancé (CO3) [1] and subsequently from Allende and Leoville (CV3; taxonomic symbols as proposed by Wasson [2]) by Lorin et al. [3]. Achondritic xenoliths within chondrites are of critical importance for our understanding of chondrite formation and the evolution of asteroids. Lithic fragments of differentiated rocks within "primitive" carbonaceous chondrites clearly demonstrate that they are even more "primitive", and that igneous activities predate the formation of complex breccia rocks like the carbonaceous chondrites (compare [4]). A major goal of the investigations of such fragments therefore is to unravel their history and to decide on petrological grounds whether they are real igneous rocks or pseudoigneous rocks like meltrocks.

We report here the results of a petrologic investigation of three basaltic lithic fragments from the

Lancé carbonaceous chondrite, designated 2LN, 3A1, and 5B, respectively, and discuss some implications for their origin.

Analytical Techniques

Microprobe analyses were performed using an ARL-SEMQ automated electron microprobe operating at 15 kV acceleration potential and about 15 nA sample current (benitoite). Because of the small grain size, all mineral analyses had to be performed with a finely focussed beam (diameter $< 0.5 \mu\text{m}$). Some decomposition of sensitive minerals by electron bombardment was unavoidable, as can be seen from the occasionally low totals of feldspar and feldspathoid analyses. The bulk composition of fragment 2LN was determined by the scanning beam technique [5]. Mineral analyses were corrected on-line according to the α -factor method by Bence and Albee [6].

Sample Descriptions

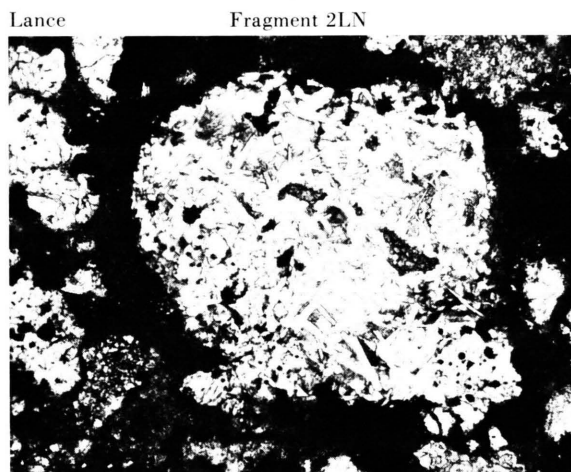
All three lithic fragments investigated in this study resemble basaltic rocks with different amounts of irregular inclusions consisting mainly of enstatite.

Reprint requests to Doz. Dr. G. Kurat, Postfach 417, A-1014 Wien.

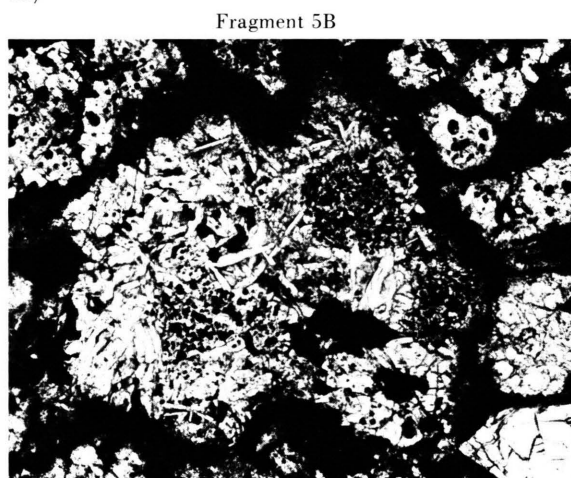
On the contact to the plagiophyric parts of the fragment, enstatite shows intergrowths with plagioclase characteristic of a cogenetic origin, and on this basis we identify these enstatites as “phenocrysts” in Table 1 and the following discussion. However, some of their features, e.g. the poikilitic (= metamorphic) intergrowth described below, can best be understood if the enstatites were xenocrysts, and we cannot rule out that they consist of xenocryst cores which served as nuclei around which additional enstatite precipitated from the basaltic melt. The following discussion should be understood keeping this qualification in mind.

Fragment 2LN

Figure 1a shows inclusion 2LN in transmitted light. Plagioclase laths occur throughout the inclusion except for two areas which consist of granular enstatite. The outlines of these areas and the optical continuity suggest that they were derived from parental single crystals. Hercynitic spinel occurs in small individual grains and two large clusters of grains, showing partial reaction with the matrix. It is enveloped by a layer of plagioclase-nepheline intergrowth. SEM pictures (Fig. 2) reveal a very intimate intergrowth on a submicron scale of two Ca-rich pyroxenes with plagioclase in the interstices of the porphyric feldspars: Fibrous ferrosalite (light phase in the SEM picture) and patchy low-Fe augite (the nomenclature is discussed below). The plagioclase is permeated by fine cracks ($\leq 0.5 \mu\text{m}$) filled with a high-Na phase (presumably nepheline),



1a)



1b)

Fig. 1. a) Basaltic lithic fragment 2LN from the Lanceé carbonaceous chondrite. Plagioclase laths are either intergrown with pyroxenes or embedded in a fibrous pyroxene plus plagioclase matrix. Enstatite phenocrysts are visible at the lower right and left ends. Irregularly outlined spinel xenocrysts (dark grey) are exposed at about the center of the fragment. Width of picture is 0.63 mm; plain polarized light. b) Basaltic lithic fragment 5B from the Lanceé carbonaceous chondrite. Plagioclase laths are intergrown either with pyroxenes or are embedded in a fibrous pyroxene-plagioclase matrix. Phenocrysts of enstatite are readily visible because of their high contents of metal and sulfide (black). Width of picture is 0.8 mm; plain polarized light.

Table 1. Textural and compositional characteristics of basaltic lithic fragments from the Lanceé carbonaceous chondrite.

	2LN	3A1	5B
Size (μm)	450×500	450×600	600×700
Basalt/“phenocryst”	≥ 1	< 1	~ 1
Metal content of “phenocrysts”	very low	high	high
Enstatite	en 98.5	en 97.5	en 98.5
Low-Fe Augite	en 53 wo 44	en 54 wo 44	en 53 wo 45
Olivine	fo 91–67	fo 60–40	fo 95–68
High-Fe Augite	en 11–20 wo 50	en 15 wo 47	n. d.
Plagioclase	an 73	an 71*	an 70
Nepheline	abundant	n. d.	n. d.
Spinel	hercynite	n. d.	n. d.

n. d. = not detected; * inferred from Al/Si ratio.

and in some places exhibits lamellar intergrowths with nepheline. Olivine is rare and very small. Its composition varies from fa9 to fa33, but in contrast to inclusion 5B, no zoning was observed. Very little metal is present. Analyses of oxygen-bearing minerals are given in Table 2, and of metal in Table 3. Olivines contain Ca at an igneous level.

Lance 2LN

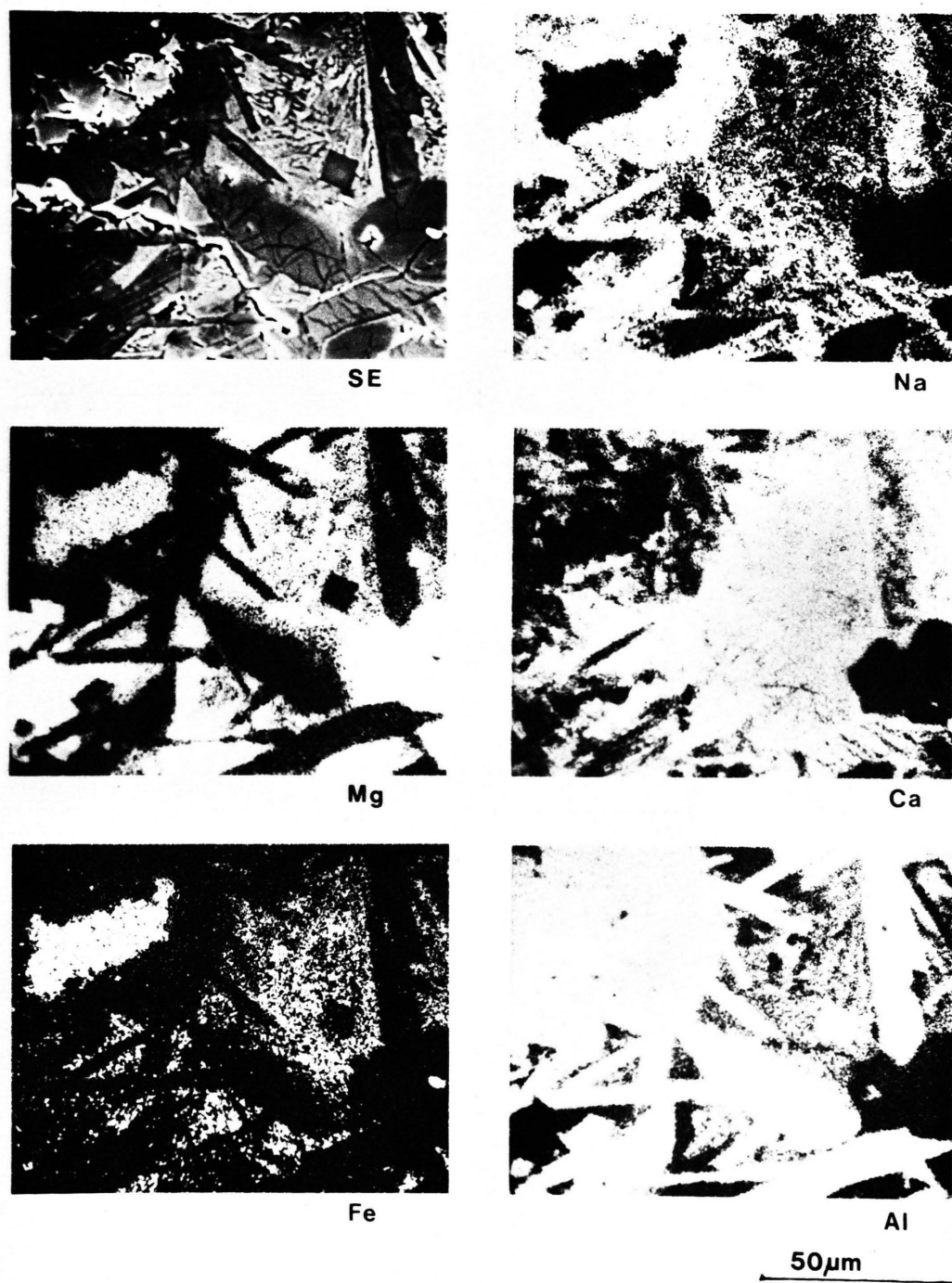


Fig. 2. Secondary electron image (SE) and X-ray scans for Na, Mg, Ca, Fe and Al of a portion of basaltic fragment 2LN from the Lanceé carbonaceous chondrite. Discussion in the text.

Table 2. Selected electron microprobe analyses of silicates from basaltic lithic fragment 2LN in Lancé.

Mineral	Olivine 1	Olivine 2	Enstatite	Augite	Ferrosaline	Plagioclase	Nepheline
SiO ₂	41.6	38.5	59.6	51.9	50.6	50.6	46.0
TiO ₂	<0.02	<0.02	0.19	3.5	0.16	0.08	0.12
Al ₂ O ₃	0.03	0.03	0.79	3.4	2.14	27.9	35.1
Cr ₂ O ₃	0.09	0.13	0.52	1.79	0.02	0.02	0.02
FeO	8.0	28.0	1.77	0.67	21.7	0.40	0.24
MnO	0.09	0.21	0.32	1.06	0.27	0.02	0.05
MgO	48.4	32.0	34.7	17.6	3.4	0.50	0.03
CaO	0.18	0.23	2.48	20.1	21.1	15.2	0.75
Na ₂ O	<0.02	<0.02	0.02	0.07	0.34	2.92	18.7
K ₂ O	<0.02	<0.02	<0.02	0.02	0.04	0.06	0.03
Total	98.39	99.10	100.39	100.11	99.77	97.68	101.02
Fe/(Fe + Mg)	0.084	0.329	0.028	0.021	0.782	0.307	0.824

Table 3. Partial analyses of metal grains from basaltic lithic fragments in Lancé.

Incl. no.	2LN			3A1	
Grain no.	1a *	1b *	2	2a *	2b *
Fe	58.0	96.0	96.3	44.53 **	95.63 **
Co	0.27	1.2	0.52	0.07	0.47
Ni	42.7	4.0	3.2	55.4	3.9
Total	100.97	101.2	100.02	100.00 **	100.00 **

* Two-phase grains; a and b following grain numbers denote different parts of the same grain.

** Fe determined by difference to 100%.

Puzzling is the presence of Cr in olivine regardless of its fo-content. Enstatite contains some Al and Ti and is also high in Cr and Ca. The low-Fe augite is high in Ti, Al and Cr, low in Ca and alkalis and has a peculiar Fe/Mn ratio of $\lesssim 1$. Ferrosalite from the matrix is almost Cr-free, low in Ti, but has some Na content. Plagioclase has about an73 and is high in Mg whereas nepheline is high in Fe and is very low in Mg and K. The Fe/(Fe + Mg) ratio of the minerals present varies over a wide range from ~ 0.02 to ~ 0.8 , but defines three mineral groups:

- (1) Fe/(Fe + Mg) $\sim 0.02 - 0.08$: low-Fe olivine, enstatite, and augite, all additionally characterized by high Cr and Mn and low alkali contents.
- (2) Fe/(Fe + Mg) ~ 0.3 : plagioclase and high-Fe olivines.
- (3) Fe/(Fe + Mg) ~ 0.8 : ferrosalite and nepheline.

The nomenclature adopted for the high-Ca pyroxenes here and in the following discussion is somewhat arbitrary, since terrestrial pyroxenes of these compositions are not known. A few of the

“ferrosalite” analyses fall into the ferroaugite field (cf. Figure 4) and the low-be pyroxene should perhaps, by purist standards, Fe referred to as “highly titaniferous aluminous chrome-diopside”, but we prefer the name augite for simplicity.

Metal compositions in fragment 2LN are given in Table 3. Most grains consist of both kamacite and taenite with, respectively, extremely low and high Ni contents.

Spinel compositions are presented in Table 4. The analyses confirm the xenocrystic nature of spinels which are Cr-poor and Fe-rich with a Fe/(Fe + Mg) ratio of about 0.6. Since the distribution coefficient of Fe between spinel and coexisting Fe-Mg silicates generally is ≥ 2 , the spinels could be genetically related to the high-Fe olivines.

The bulk composition of the basaltic portion of fragment 2LN (including spinels) was determined by scanning beam microanalysis. Similarly, the

Table 4. Average composition, compositional range, and formula of spinel in fragment 2LN from the Lancé carbonaceous chondrite.

	Average of 5	Range	Cations per 4 O	
SiO ₂	0.25	0.13 – 0.36	Si	0.007
TiO ₂	1.29	0.40 – 1.65	Ti	0.027
Al ₂ O ₃	57.8	57.2 – 58.4	Al	1.885
Cr ₂ O ₃	1.30	0.39 – 2.82	Cr	0.028
V ₂ O ₃	0.51	0.46 – 0.59	V	0.011
FeO	26.4	25.5 – 27.6	Fe	0.611
MnO	0.12	0.09 – 0.17	Mn	0.003
ZnO	0.33	0.22 – 0.41	Zn	0.007
MgO	10.2	9.5 – 10.8	Mg	0.421
CaO	0.11	0.07 – 0.16	Ca	0.003
Total	98.31		M ³⁺ + M ⁴⁺	1.958
			M ²⁺	1.045
			Total	3.003

matrix portions in between plagioclase laths were also analyzed. The results are given in Table 5. The bulk composition of the basaltic portion clearly is alkali-olivine basaltic whereas the matrix composition is nephelinitic. The overall Fe/(Fe + Mg) ratios of the whole basalt portion and the nephelinitic matrix are both highly dominated by dispersed enstatite and low Fe/Mg augite grains and therefore are not suitable for estimates of the degree of fractionation of the basaltic melt.

Fragment 3A1

Most of this fragment consists of granular and single crystal enstatites similar to those found as a major constituent in fragment 2LN (compare Table 1). Enstatites in 3A1, however, contain abundant patches of metal and some sulfide (Figure 3). The enstatite grains are outlined by an outer zone enriched in Fe and Ca which can clearly be seen in Figure 3. These Fe-rich zones, however, are much too thin ($< 0.5 \mu\text{m}$) for analysis.

Two areas of $\sim 100 \mu\text{m}$ in diameter exhibit the typical plagioclase-phyric and ophitic texture. Minerals in these areas are similar to those in fragment 2LN, but nepheline and spinel are absent. Electron microprobe analyses of silicates from fragment 3A1 are given in Table 6. "Plagioclase" analyses, however, do not fit any formula, although this phase exhibits a weak birefringence. The proportions of Si : Al : Ca : Na are incompatible with plagioclase or any other known feldspar or foidite mineral. From its morphology it clearly was plagioclase originally,

Table 5. Bulk compositions of the basaltic portion of fragment 2 LN in Lancé and the igneous matrix within fragment 2 LN.

	Composition			CIPW norm	
	Frag- ment	Matrix		Frag- ment	Matrix
SiO ₂	50.6	47.5	ilm	1.06	0.20
TiO ₂	0.79	0.15	chr	0.51	0.22
Al ₂ O ₃	17.9	29.6	ab	21.36	12.20
Cr ₂ O ₃	0.48	0.17	or	1.90	4.20
FeO	4.3	0.86	an	28.94	25.32
MnO	0.33	0.05	ne	8.00	48.27
MgO	8.9	2.91	cpx	26.05	5.48
CaO	12.8	7.1	ol	12.20	4.11
Na ₂ O	4.0	11.3			
K ₂ O	0.39	0.78	Fe/(Fe + Mg)	0.21	0.11
Total	100.49	100.42			

Table 6. Electron microprobe analyses of different minerals from basaltic lithic fragment 3A1 from the Lancé carbonaceous chondrite.

	"Plagioclase"		Enstatite	Augite	Ferrosal.
No of analyses	extremes of 7 analyses		6	2	2
SiO ₂	48.1	49.8	60.2	54.0	51.9
TiO ₂	0.05	0.03	0.13	1.12	0.07
Al ₂ O ₃	30.6	32.3	0.72	3.2	1.02
Cr ₂ O ₃	—	—	0.55	1.27	0.06
FeO	0.53	0.44	0.87	1.01	20.7
MnO	—	—	0.05	0.52	0.15
MgO	0.25	0.46	38.5	20.2	8.5
CaO	6.1	10.1	0.70	19.4	17.9
Na ₂ O	11.0	5.7	0.06	0.05	0.56
K ₂ O	1.04	0.60	0.02	0.04	0.05
Total	97.69	99.43	101.78	100.83	100.91
Fe/(Fe + Mg)	0.542	0.348	0.012	0.027	0.576

and using the Al/Si ratio the same an-content of about 71 is obtained as observed in 2LN and in the stoichiometric feldspars in 5B. It has to be kept in mind here that in lunar plagioclase an-contents calculated from Al/Si ratios generally differ from those calculated from Na/Ca ratios [7]. In our case, however, the nonstoichiometry is of a different nature than in lunar plagioclase, and we regard it as the result of alteration during a metasomatic process which added primarily Na and K and removed Ca without gross alteration of the anorthitic crystal framework. Since this replacement process is not known from terrestrial plagioclases, this explanation is somewhat speculative but could be envisaged for a water-free environment. The enstatites, which are partly intergrown with "plagioclase", are constant in composition except for a very thin outer rim. They contain some Ti, Al, Mn, Na, and are rich in Cr — almost identical to the enstatites in fragment 2LN. The Ca content, however, differs in being much lower in enstatites from 3A1 than in those from 2LN. Low-Fe augites which are present within the basaltic portions are again rich in Ti, Al, and Cr and poor in alkalis. This augite again is rich in Mn displaying a strongly fractionated Fe/Mn ratio.

Ferrosalite dominates the finegrained matrix — as in 2LN. It is poor in Ti and Cr and has some alkali content. Olivine (not presented in Table 6) is finegrained and has fa40 to fa60.

Typical compositions of metal from a composite grain are given in Table 3. Taenite and kamacite again are extreme in their Ni contents. Associated

Lance 3A1

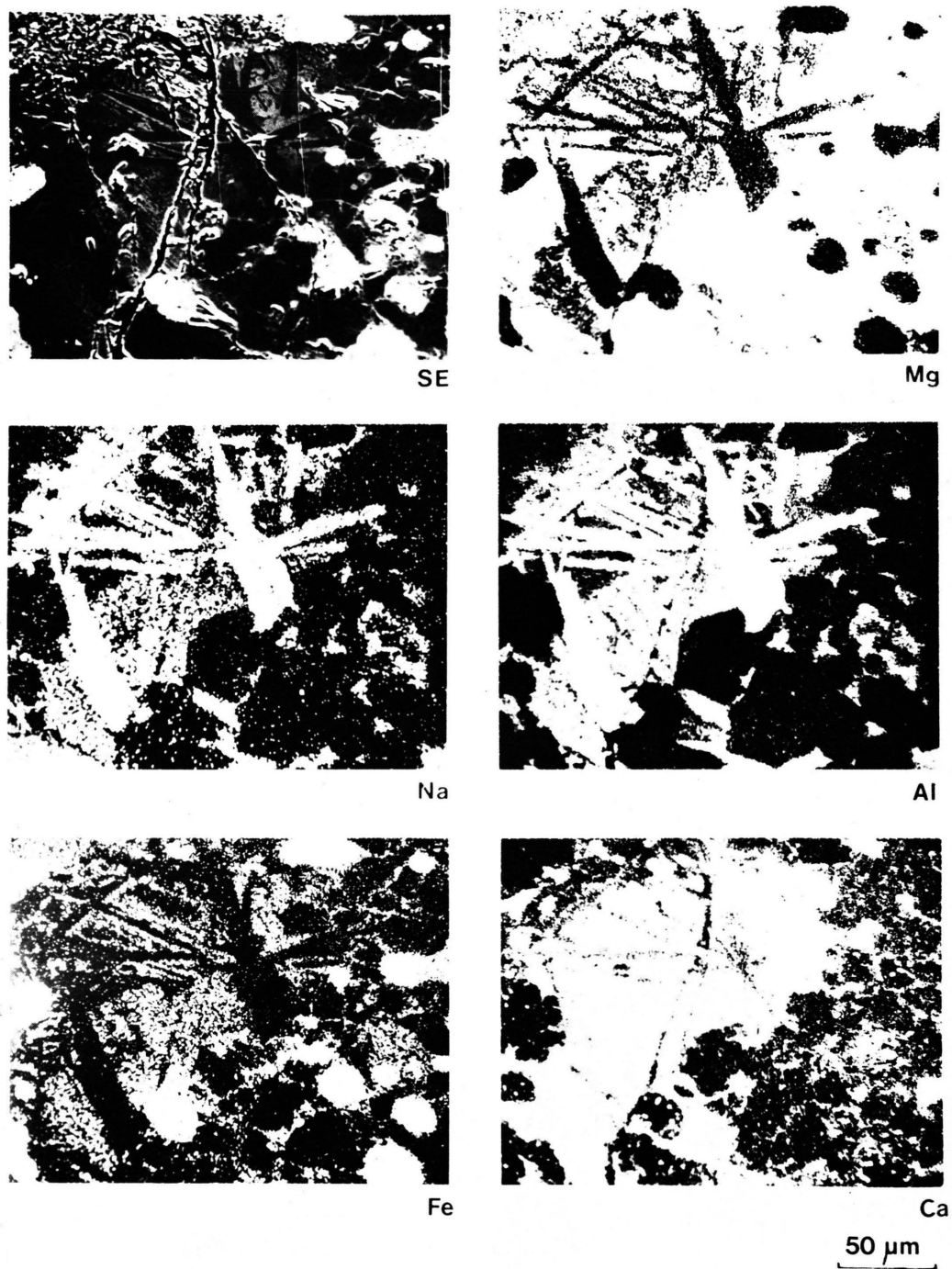


Fig. 3. Secondary electron image (SE) and X-ray scans for Mg, Na, Al, Fe, and Ca of a portion of basaltic fragment 3A1 from the Lancé carbonaceous chondrite. Discussion in the text.

with the metal is very fine-grained Ca-phosphate, which however was too small to be analyzed quantitatively.

Fragment 5B

Plagiophyric portions and enstatite phenocrysts have approximately equal abundances in fragment 5B (compare Fig. 1b and Table 1). The igneous matrix between plagioclase grains is very fine-grained and appears to be chilled. Enstatites are rich in metal and sulfide blebs like those of fragment 3A1. Some sulfide and metal is also present in the plagiophyric parts. Mineral compositions (Table 7) differ somewhat from those of fragments 2LN and 3A1. Enstatite compositions vary and change to higher Fe/(Fe + Mg) towards grain surfaces. The low-Fe central grain composition is given in Table 7. Its composition is very similar to those of fragment 3A1. Low-Fe augites are rare and have very small grainsizes. The general characteristics are similar to those observed on low-Fe augites in other fragments: They are rich in Al, Ti, Cr, and Mn, and have a low Fe/(Fe + Mg) ratio. Sodium, however, appears to be appreciably higher ($\sim 0.3\%$ Na₂O) than in other low-Fe augites. Instead of a high-Fe augite a pigeonite is present in fragment 5B which, however, does not reach the high Fe/(Fe + Mg) ratio of ferrosalites from other basaltic fragments. Ferrosalite did not develop in 5B because the late crystallizing Ca-rich pyroxene of the matrix is missing. The matrix now is cryptocrystalline and apparently represents mostly devitrified glass. The composition

of this final melt ("matrix" in Table 7) is rich in CaO and Al₂O₃, as well as several minor elements. The normative composition is basaltic (plag $\sim 36\%$, cpx $\sim 51\%$) and slightly oversaturated ($\sim 4\%$ qu). The high Fe/(Fe + Mg) ratio suggests some metasomatic alterations, the amount of which, however, cannot be estimated.

Plagioclase appears to be somewhat altered and partly displays nonstoichiometric compositions like in fragment 3A1. The low-Na compositions, however, fit the plagioclase formula and are therefore considered being representative of the original igneous composition (Tables 1 and 7). Minor element contents are high and probably reflect igneous temperatures. Olivines occur as poikilitic inclusions in enstatite. They are compositionally zoned from fa5 (center) to fa43 (rim). Apparently, this zoning is of secondary (metasomatic) origin. Minor element contents in olivines are rather high, reflecting igneous temperatures. Notable is the presence of Cr which apparently reflects special crystallization conditions.

Discussion

All three fragments described above show clear textural evidence for an igneous origin (compare Figures 1–3). Mineral associations (Plag + Opx + Cpx \pm Ol) and bulk chemical data (Table 5) indicate a basaltic liquid composition. Mineral compositions, however, are not consistent with a simple single stage igneous origin. Elemental ratios (Fe/

Table 7. Selected electron microprobe analyses of minerals and igneous matrix from basaltic fragment 5 B from the Lancé carbonaceous chondrite.

	Olivine		Enstatite	Pigeonite	Augite	Plagioclase	Matrix
	Core	Rim					
SiO ₂	42.2	37.4	58.8	54.2	51.9	50.6	54.0
TiO ₂	0.02	0.05	0.16	0.65	3.5	0.03	1.04
Al ₂ O ₃	0.04	0.18	1.08	3.6	3.9	31.5	10.3
Cr ₂ O ₃	0.07	0.20	0.64	0.93	1.51	0.03	0.33
FeO	5.0	33.1	0.81	4.9	0.83	0.83	8.8
MnO	0.05	0.23	0.08	0.23	0.41	0.02	0.21
MgO	53.4	28.6	38.3	25.0	17.4	0.79	7.0
CaO	0.15	0.74	0.61	6.9	20.5	15.4	16.9
Na ₂ O	<0.02	<0.02	0.10	1.38	0.28	3.5	1.7
K ₂ O	<0.02	<0.02	<0.02	0.19	0.04	0.21	0.05
Total	100.91	100.50	100.66	98.0	100.27	102.91	100.33
Fe/(Fe + Mg)	0.050	0.394	0.012	0.099	0.026	0.373	0.414

Mg, Fe/Mn) and minor element contents (Ti, Cr, alkalis) of minerals indicate strong disequilibrium between coexisting minerals which cannot be explained by fractional crystallization. By taking the Fe/Mg ratio of Fe-Mg minerals four groups can be distinguished (see Figure 4) :

- 1) The very low Fe/Mg enstatites and augites ($\text{Fe}/(\text{Fe} + \text{Mg}) \sim 0.012 - 0.028$).
- 2) The high Fe/Mg pyroxenes of the fibrous to cryptocrystalline matrices ($\text{Fe}/(\text{Fe} + \text{Mg}) \sim 0.58 - 0.78$).
- 3) The spinel xenocrysts of fragment 2LN, whose $\text{Fe}/(\text{Fe} + \text{Mg})$ ratios (0.59) do not fit an elemental equilibration with any Fe-Mg silicate present.
- 4) Olivines show grain to grain compositional variations or compositional zoning within grains and vary in $\text{Fe}/(\text{Fe} + \text{Mg})$ ratio from 0.05 to 0.6.

Taking into consideration some minor element contents some relationships become apparent. Titanium contents are high in the low Fe/Mg mineral group and low in the high Fe/Mg group. The same holds for Cr which in addition is also present in olivine. This finding supports the textural evidence (poikilitical inclusion of olivine in enstatite) for a genetic relationship between enstatite and olivine. It should also be noted that Cr normally is not present in detectable amounts in olivines of chon-

drules and lithic fragments of most chondritic meteorites but it is present in olivines from highly reduced chondrules and lithic fragments in the Lancé carbonaceous chondrite [4]. The high Cr contents of the low Fe/Mg pyroxenes and the appreciable amounts of Cr in olivines is considered to represent a genetic link. Cr and Ti distribution between the two low-Fe pyroxenes are consistent with their crystallization from the same melt.

Manganese behaves rather strangely. The Fe/Mn ratios vary over more than two orders of magnitude. Low Fe/Mg augites have Fe/Mn ratios of 0.63 to 2.03, enstatites between 5.6 to 17.5, ferrosalites and olivines between 80.7 and 144 (approximately chondritic) and spinel xenocrysts around 220. This extreme Fe/Mn fractionation cannot be explained by a simple igneous fractionation process. It rather reflects different processes and/or sources of Fe and Mg. Surprisingly, the low-Fe/Mg mineral suite varies widely in Fe/Mn ratio, although other minor elements and textural relationships strongly suggest a genetic link. The lowest Fe/Mn ratio is found in low-Fe augite, which is a late crystallizing phase filling interstices between plagioclase laths. The strong Fe/Mn fractionation through the sequence olivine \rightarrow enstatite \rightarrow low-Fe augite can only be explained, if a selective Fe-removing process accompanied crystallization. The only process we can think of is reduction and partial removal of oxidized Fe during crystallization. Alkali contents of low Fe/Mg phases are generally low, but high Fe/Mg augites contain appreciable amounts of Na and also some K.

Plagioclase compositions are somewhat puzzling because they do not in all instances fit the plagioclase formula. Low alkali compositions, if present, are between an70 and an73 and fairly constant. Most of the plagioclases, however, show excess Na and K contents but Al/Si ratios which correspond to \sim an70. Partial replacement by and intimate intergrowth of plagioclase with nepheline (fragment 2LN) strongly suggest a metasomatic alteration by Na-rich fluids or vapours. This process can clearly be seen in Figure 2, where plagioclase laths are strongly enriched in Na along cracks and partly have been converted to nepheline. Because of the open framework structure of plagioclase it probably is strongly receptive to exchange reactions and therefore probably has retained little information on the igneous crystallization event. Beside the strong tex-

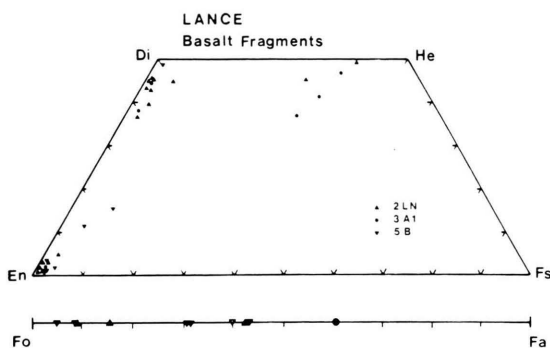


Fig. 4. Pyroxene compositions of basaltic lithic fragments from the Lancé carbonaceous chondrite in the pyroxene quadrilateral (molecular proportions) and olivine compositions expressed as mole-% fo (bottom).

tural evidence for coprecipitation of plagioclase and enstatite, and plagioclase and low Fe/Mg augite, the generally high Mg and detectable Ti contents of plagioclases probably reflect this event. The Fe/Mg ratio, however, has partly been changed by metasomatic addition of Fe and cannot be regarded as representing the original igneous ratio.

Nepheline is only present in fragment 2LN and apparently is an alteration product after original plagioclase. Its composition is remarkable in being almost K-free. This is suggestive of an altering fluid or vapour having a high Na/K ratio. Spinels in fragment 2LN apparently are not related in any way to any of the minerals present except for the fact that they are enveloped by Al-rich halos consisting of plagioclase and nepheline which separate them from the pyroxenes. Spinels in 2LN apparently are xenocrysts which partly reacted with the melt leading to preferential formation of plagioclase in their vicinity. The low Cr content is incompatible with an origin from the Cr-rich basaltic melt as are the Fe/Mg and Fe/Mn ratios. Furthermore, no relationships to any other phases present are apparent and the spinels in fragment 2LN therefore must be regarded being real xenocrysts of unknown origin. They may, however, be related to hercynites found in altered Ca-Al-rich inclusions [8].

The observed igneous lithic fragments described here are dominated by a liquid of basaltic composition. The bulk composition of the original melt cannot be established for various reasons:

- 1) We do not know whether all enstatite present has precipitated from the melt, or part of it is xenolithic.
- 2) The ratio of enstatite to the plagiophyric melt portion observed in the inclusions need not be indicative of that in the original melt. On the contrary, the variability of this ratio suggests that the inclusions may at least in part be fragments of an enstatite-rich cumulate.
- 3) Metasomatism has extensively altered the bulk composition by adding alkalis, Fe, and presumably some mobile minor elements. For example, the Fe/Mn ratio of high-Fe olivines and olivine rims is not much higher than the chondritic ratio, indicating that Fe and Mn have probably been added in roughly that proportion.

Some inferences concerning that basaltic melt can nevertheless be drawn from mineral compositions and the composition of the residual melt. Plagioclase compositions indicate that it was enriched in Al and had a low Ca/Al ratio. If Fe-poor olivines now poikilitically included in enstatite and olivine cores represent the original liquidus phase, then the Fe/Mn ratio of the melt was not less than $0.5 \times$ chondritic, i.e. the melt was initially not extremely reduced. Alternatively, olivines could be xenocrysts not related to the basaltic melt. In either case, however, Fe was subsequently removed by continuous reduction to Fe^0 during crystallization of either enstatite alone or enstatite plus plagioclase. This process, reflected in the low Fe/Mn ratio of the late crystallizing low-Fe augite, led to the separation of two liquids (metal and silicate). It also may have lowered the M^{2+}/Si ratio sufficiently to make enstatite rather than olivine the liquidus phase, thus explaining the scarcity of olivine, and its absence from the later, more reduced paragenesis. Enstatite started to crystallize early and incorporated both olivine and metal drops. This process was probably enhanced by the reduction reaction, since removal of FeO from the melt raised its liquidus temperature. Finally, plagioclase of bytownitic composition (an70 to an73) appeared at the liquidus. There is clear textural evidence of coprecipitation of plagioclase and enstatite (see Figures 1–3). Crystallization of plagioclase lead to a dramatic increase of minor element contents of the residual melt. Titanium, Cr, and Mn — which in contrast to Fe are not accepted by the plagioclase lattice — became highly enriched. The late clinopyroxenes crystallizing from that melt are correspondingly enriched in these elements and are also characterized by an extreme Fe/Mn ratio (around 1). This crystallization sequence is consistent with a melt containing moderately volatile elements in nearly unfractionated amounts relative to one another but which was enriched in refractories. The nature of the reducing agent remains unclear, but if, as discussed above, the starting material is represented by a liquid in equilibrium with olivine compositions such as given in Table 7 (col. 1), reduction must have been an efficient process involving considerable mass transport during removal of excess oxygen. The same process may have reduced some chromium to Cr^{2+} and titanium to Ti^{3+} . These valency states are in accordance with

the cation balance in late crystallizing low-Fe augite and with the geochemical behaviour during melt evolution. Incipient reduction could also explain the presence of some Cr in olivine, and the conspicuous absence of Cr-spinel from the magmatic mineral suite.

The highly variable enstatite/residual melt ratios of the three fragments could be the result of different amounts of cumulate formation. Thus, sample 3 could represent a cumulate rock and sample 2 a rock dominated by the residual melt.

Before or after incorporation of the rock fragments into the Lancé chondrite they suffered an intense metasomatic alteration which mainly affected the framework-structured plagioclase and the orthosilicate olivine. Of the pyroxenes only the finegrained matrix pyroxenes have been affected. This metasomatic event added mainly Na and Fe to the system and caused formation of nepheline and non-stoichiometric plagioclase, high Fe/Mg augites, and zoning of olivines and enstatites. Because of the non-stoichiometric composition of plagioclase not yet observed in terrestrial rocks the metasomatism probably took place without action of H₂O. A H₂O-free vapour phase or an alternative liquid could have been responsible for the mass transport. Similar metasomatic processes have been observed in other lithic inclusions in Lancé [4, 8] and other chondrites [9, 10].

Speculations

Perhaps the most important question posed by the discovery of the basaltic fragments in Lancé is whether they could have formed from an internally-derived melt rather than an impact melt pool. Genuine magmatic activity on some precursor of the CO parent body is irreconcilable with the prevalent view of carbonaceous chondrites as being composed exclusively of primitive material, altered only after the meteorite parent bodies had accreted. From the planetological viewpoint, therefore, an impact melt origin is much more plausible. Speculations on the genesis of the basaltic liquids would be premature at this stage, but as discussed below most of the evidence is difficult to explain by an impact origin.

The composition of the melt is unlike any known meteorite type. The measured bulk composition of fragment 2LN (Table 5) does not fall within the ranges of either chondrule or fragment compositions

of carbonaceous chondrites [11]. On the other hand, all three fragments found in three different thin sections exhibit very similar characteristics. This, together with the peculiar melt composition, makes it very likely that they are derived from the same source. It is particularly puzzling that the Allende and Leoville meteorites, belonging to a different class (*viz.*, CV), contain similar although not identical inclusions [3]. Impact melt rocks do exist in ordinary chondrites [12–15], but they are derived from the host rock, and in most cases bear no textural resemblance to the basaltic inclusions in Lancé. In the latter, the chemical variations between corresponding minerals in different inclusions, the incipient cumulate formation, the reduction reaction concomitant with crystallization, as well as a number of other features can only be understood if the original magma reservoir was rather large. No inferences can be drawn about the size of impact melt pools existing on the parent bodies of ordinary chondrites, but since readily apparent meltrock clasts are generally small and rare, the amount of parent melt may have been small as well.

The only model specifically requiring melt-pools on meteorite parent bodies of at least whole-meteorite size is that proposed for the origin of group IAB iron meteorites by Wasson *et al.* [16]. In this case, however, the melt is metallic, and significantly lower temperatures (by at least 500 K) are involved; therefore the scenario adopted there has little bearing on the genesis of the basaltic inclusions.

The unique properties of the Lancé basaltic inclusions seem to point to an origin by partial melting of a source rock, which was

- 1) enriched in refractory elements as compared to chondritic composition (high Ca, Al plagioclase),
- 2) depleted in volatiles (Na, K, S; all primary silicates are low in alkalis), and
- 3) contained moderately volatile elements (Cr, Mn) in approximately chondritic abundances relative to one another.

From this first detailed investigation of basaltic fragments in the Lancé carbonaceous chondrite we realize to be far from being able to give final answers to the questions arising from our findings. Minor and trace element and isotopic studies eventually could lead to some ideas concerning the origin of these early basaltic melts.

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