

# The Kangean and Kediri, Indonesia meteorites

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## Abstract

Two meteorite falls in Indonesia were described and classified. Kangean has  $Fe/Si = .73$ , olivine  $Fo = 17.5$  with 1.7 Percent Mean Deviation, paucity of clinopyroxene, plagioclase, and glass and with weakly undulose olivine, and is classified as H5b. Mineralogically Kediri is unshocked and shows virtually no signs of metamorphic reequilibration although the mineral chemical evidence is ambiguous. Classification of Kediri as L3a is proposed. Kediri contains grains that may have survived chondrule formation without melting, and shows evidence for hot accretion.

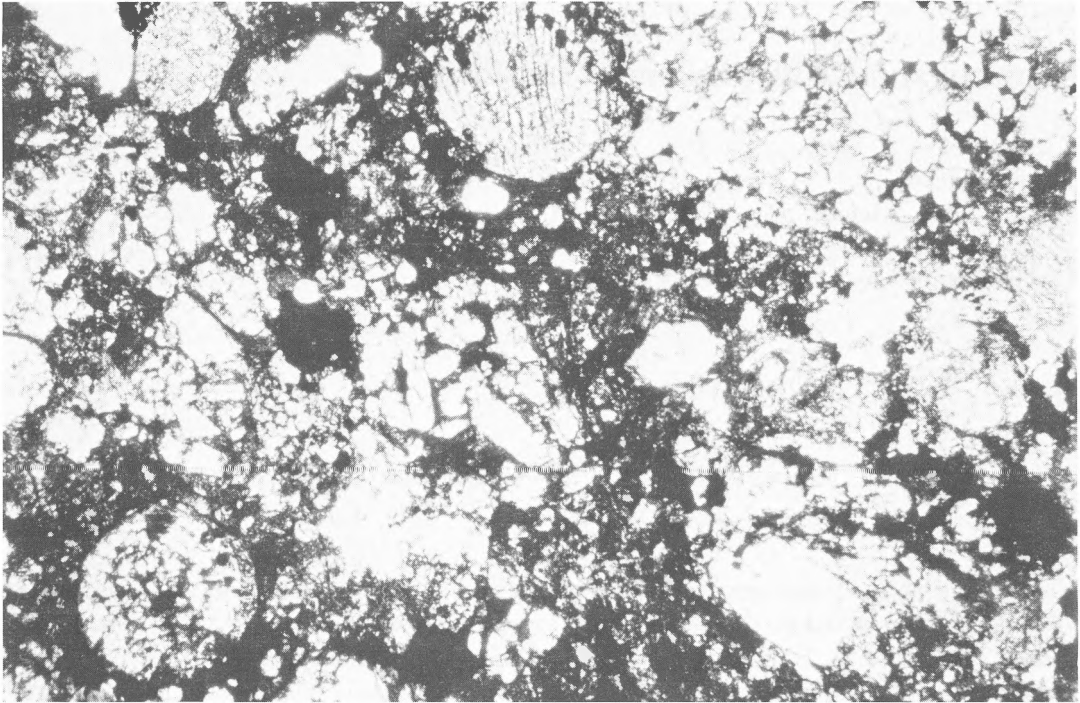
## Introduction

During the preparation of a catalogue of meteorites in Dutch collections (Van Calsteren 1979) two specimens were found that had not been described following current classification schemes. The Kangean meteorite has been described petrographically in great detail, (Niggli 1966), but without microprobe analyses of the silicates. The fall of the Kangean meteorite was witnessed on the 27th November 1908 (not *September* as in the Catalogue of Meteorites, 4th Edition, Graham et al. 1985) in a submerged sawah near Kampong Se Djabang, Kangean Island, North of Bali, Indonesia. The single stone recovered, weighing around 1650 gr, was broken by the local population and is fairly oxidised for an immediately recovered fall. The broken pieces were stuck together and make a fine specimen in the collection of the Mineralogical Geological Museum, Delft, The Netherlands. On the lenticular shape clear piezoglyphs marks the leading face during atmospheric entry, while

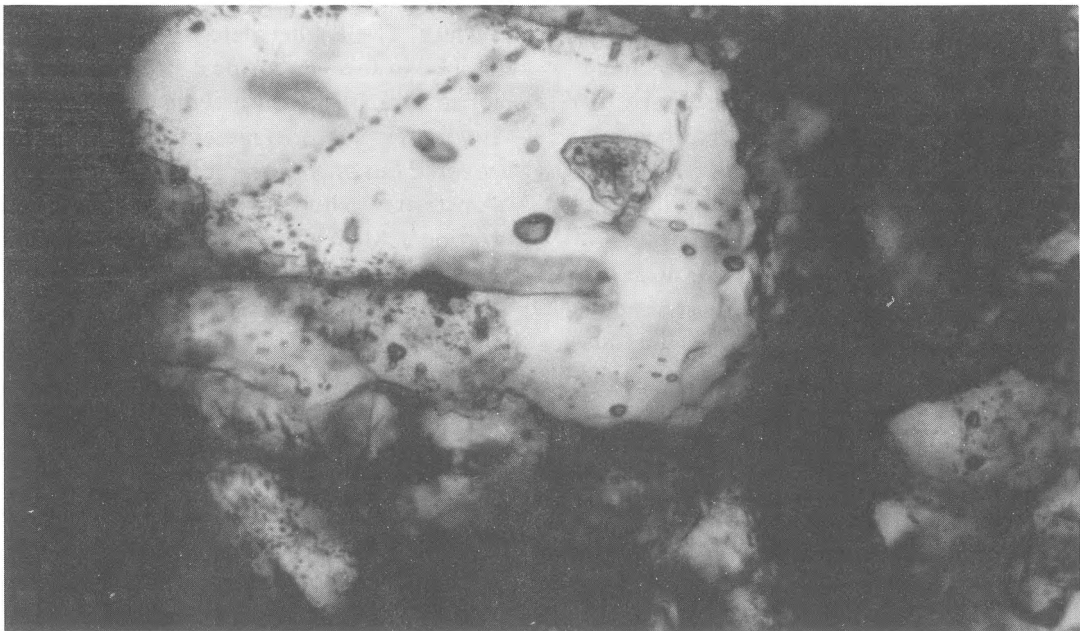
strung-out melt droplets occur on the posterior surface. The Kediri meteorite has been briefly described in the Meteoritical Bulletin 53, (1975) and fell in 1940, 10 km south of the town of Kediri, Java, Indonesia. Some 70 meteorite fragments were recovered but only the largest of 3404 gr was taken to Amsterdam where it was cut and distributed. In the National Museum of Geology and Mineralogy a new thin section was made of a 174 gr specimen in the collection of the Teyler Museum in Haarlem, the Netherlands.

## Kangean texture

In thin section chondrule and chondrule fragments are obvious (Figure 1), they are set in a recrystallised matrix of orthopyroxene and olivine with an average grain size c.  $80 \mu m$ . Some low Ca orthopyroxenes have inclusions up to  $10 \mu m$  long that apparently contain a fluid or a vacuum (Roeder 1984) (figure 2). A few twinned clinopyroxene



*Fig. 1.* Overview of Kangean, transmitted plane light, field of view 5.4 mm; porphyritic and barred chondrules are clearly visible in recrystallized matrix; dark parts are metal and troilite with some secondary oxidation.



*Fig. 2.* Kangean orthopyroxene grains with both individual and trails of apparent fluid inclusions; field of view 15  $\mu\text{m}$ , transmitted plain light.

grains have been found but no plagioclase or glass, only micro-crystalline aggregates that could be either plagioclase or glass or both. The larger olivine grains in the matrix are cracked and some show slight undulose extinction. The meteorite is therefore assigned to shock facies 'b' of Dodd & Jarosewich (1979) following the practice of Ehlmann & Keil (1985) of extending this classification to all chondritic meteorites. Metal grains consist of kamacite and taenite, in variable proportions. Most grains contain a few percent taenite while some, or even domains within grains, have roughly equal quantities of these two minerals. Metal and troilite are equally abundant and troilite is usually crystallographically continuous. Some troilite grains contain numerous granular silicate matrix grains and have clearly been mobile at a stage when silicates were rigid (figure 3). Boundaries between the 0.3–1.3 mm chondrules and the matrix are mostly sharp and well defined, but the smaller rather finer grained olivine chondrules are more difficult to discern. Most olivine chondrules are barred or por-

phyritic, and about a quarter of the total consist of radiating low Ca pyroxene.

### Kangean composition

Two whole-rock chemical analyses have been carried out at the Geological and Mineralogical Institute in Leiden. Results of a 1949 gravimetric analysis (Niggli 1966) are listed in full in Table 1<sup>a</sup>, together with a partial analysis using atomic absorption and spectrophotometry performed in 1979. The agreement is satisfactory considering the evolution in analytical techniques as well as the change in personnel. The presence of significant amounts of H<sub>2</sub>O and Fe<sub>2</sub>O<sub>3</sub> confirms that the sample is slightly weathered. The Fe/Si (atom ratio) = .73 puts Kangean in the chemical H group (Van Schmus & Wood 1967). If Fe<sub>2</sub>O<sub>3</sub> is combined with Fe the Fe red/Si = .37 and Fe ox/Si = .40 similar to these values for Tieschitz (H3) (Wasson 1974), but different from the main group of H meteorites.

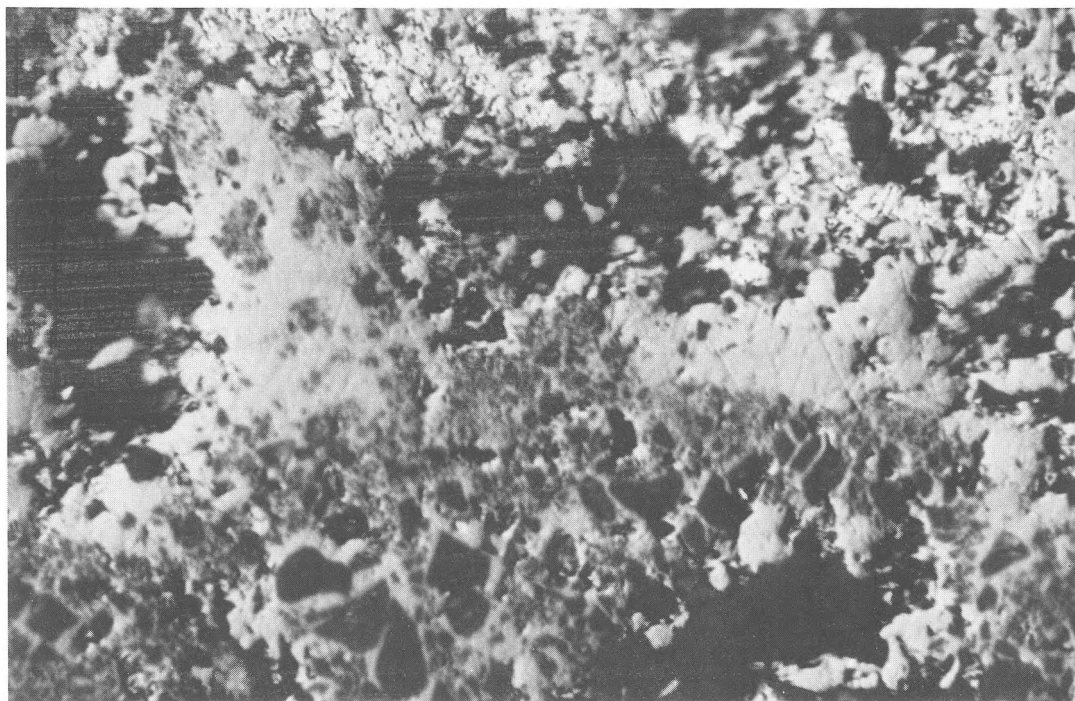


Fig. 3. Kangean silicate grains, dark grey, incorporated in troilite, light grey, which is also intimately intergrown with white metal in the lower third of the picture; field of view 15  $\mu$ m, reflected plane light.

Table 1a. Chemical analyses of Kangean chondrite. Whole rock analyses on c. 200 mg powder; 1949 and 1979 indicate the years in which the analyses were made.

	1949	1979
SiO <sub>2</sub>	34.89	36.17
TiO <sub>2</sub>		.13
Al <sub>2</sub> O <sub>3</sub>	3.07	1.56
Fe <sub>2</sub> O <sub>3</sub>	1.20	37.96*
FeO	15.79	
Fe	12.68	
MgO	23.18	22.20
MnO	.20	.27
CaO	2.15	1.65
Na <sub>2</sub> O	1.35	1.01
K <sub>2</sub> O	.73	.18
H <sub>2</sub> O	.96	
S	1.99	
Ni	2.17	1.08
P <sub>2</sub> O <sub>5</sub>		.30
Total	100.36	102.51

\* total Fe

Table 1b. Electron microprobe analyses of individual grains in thin section D14689; errors are one standard deviation.

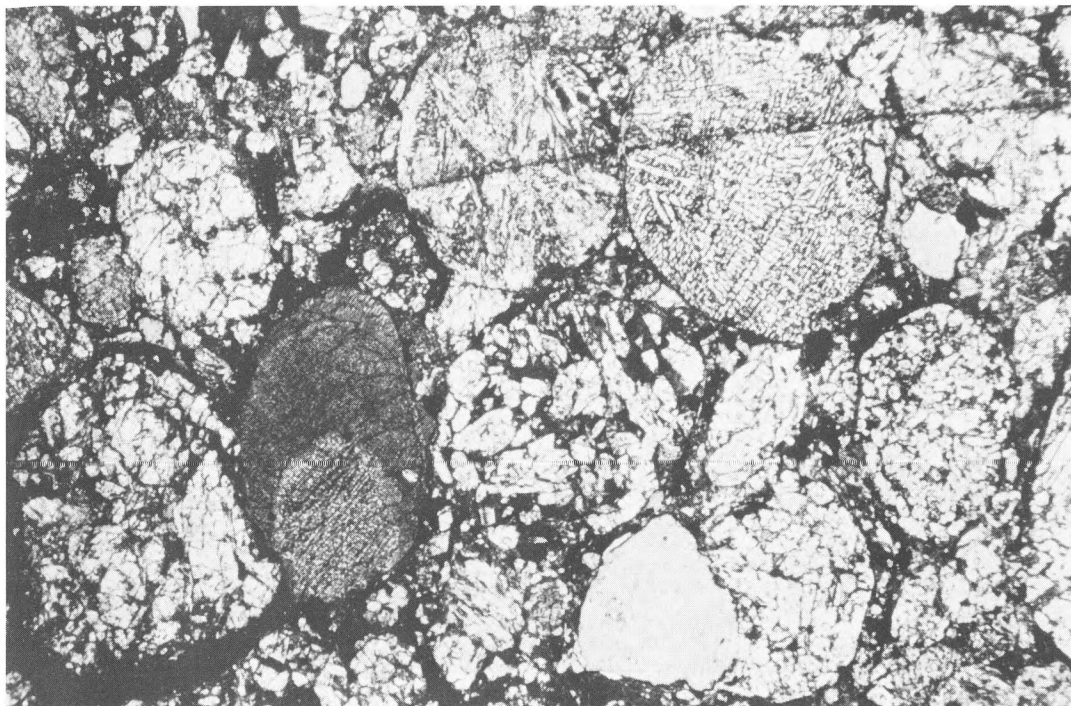
	Olivine	$\sigma$	Opx	$\sigma$
SiO <sub>2</sub>	39.67	.35	54.39	2.3
TiO <sub>2</sub>	.05	.04	.24	.1
Al <sub>2</sub> O <sub>3</sub>	.05	.08	.71	.5
FeO	17.72	.26	11.71	.9
MnO	.47	.02	.49	.0
MgO	42.81	.67	31.41	1.5
CaO	.13	.39	.69	.1
Na <sub>2</sub> O				
Cr <sub>2</sub> O <sub>3</sub>			.31	.2
Total	100.90		99.95	
No. of analyses	21		12	

Recombining Fe<sub>2</sub>O<sub>3</sub> with FeO does not make a significant difference and since the total Fe<sub>2</sub>O<sub>3</sub> contents in both analyses are in agreement, analytical error is unlikely, but terrestrial oxidation cannot be ruled out. Alternatively, it could be that some H group meteorites are intrinsically more oxidised than others, although apart from Castalia, all other

relatively oxidised chondrites are unequilibrated (Wasson 1974). Electron microprobe analyses at the Open University using 20 kV acceleration potential with 30 nA beam current and a slightly defocused beam were carried out on olivine, low Ca pyroxene and glass. Means and standard deviations are reported in Table 1b and only analyses with totals between 98% and 101% and good stoichiometry are included. The Fa = 18.7 in olivine and Fs = 17.5 in low Ca pyroxene are identical to Niggli's (1966) determination using optical and X-ray parameters, and confirm the H group classification (Van Schmus & Wood 1967). Percentage Mean Deviations of 1.7 and 2.0 for olivine and low Ca-pyroxene, respectively, indicate that these minerals are equilibrated both in chondrules and matrix. The rare occurrence of monoclinic pyroxene and the absence of clear plagioclase and glass put Kangean in petrological type 5.

### Kediri texture

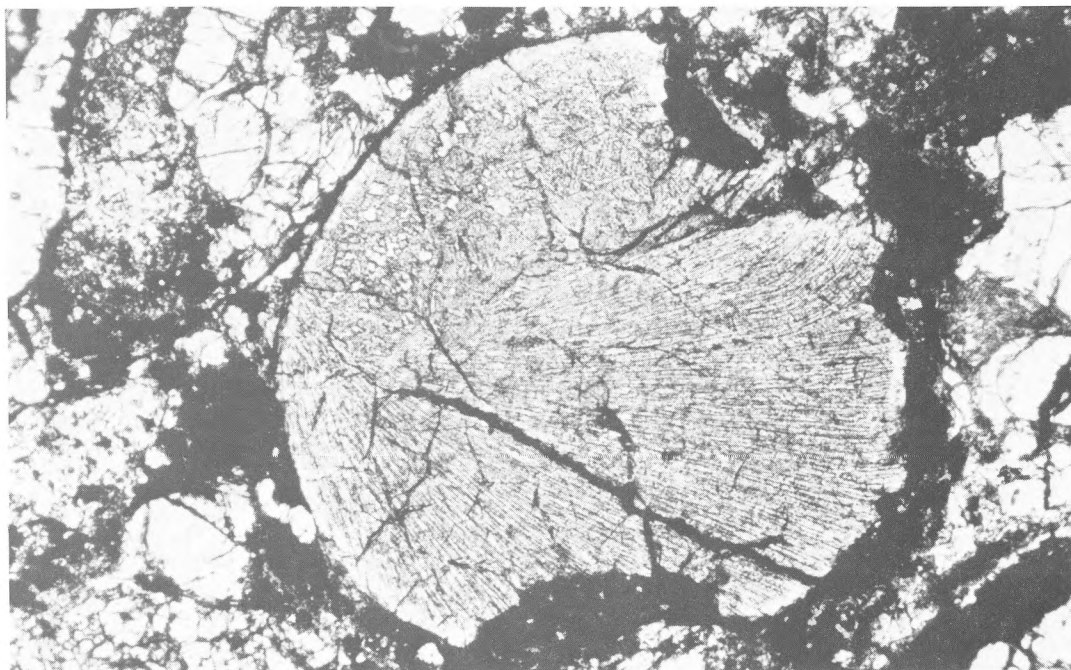
In thin section (Figure 4) this sample consists almost entirely of chondrules and chondrule fragments with only a few percent of matrix. This matrix consists principally of isotropic glass containing minute crystallites, probably pyroxene. The matrix has taken on a slight iron oxide stain which makes it easily distinguishable. Some chondrules have fine grained dark rims, while others have acquired a decoration of troilite and metal and the glassy matrix is clearly visible outside this rim. Chondrules are somewhat oblate in shape with the long axes parallel and they appear to have been slightly squashed while still plastic after agglomeration. Shock reheating after solidification as advocated by Wasson (1985) for Leoville (CV3) seems implausible since this would surely result in the destruction of delicate quench textures and a higher degree of equilibration. The complex construction of some chondrules (Figure 4) may be interpreted as resulting from the expulsion of some liquid. Similar textures as in Figure 4 have been interpreted as resulting from the collision between two or more liquid chondrules in free space (Keil et al. 1978). Other chondrules show equigranular poly-



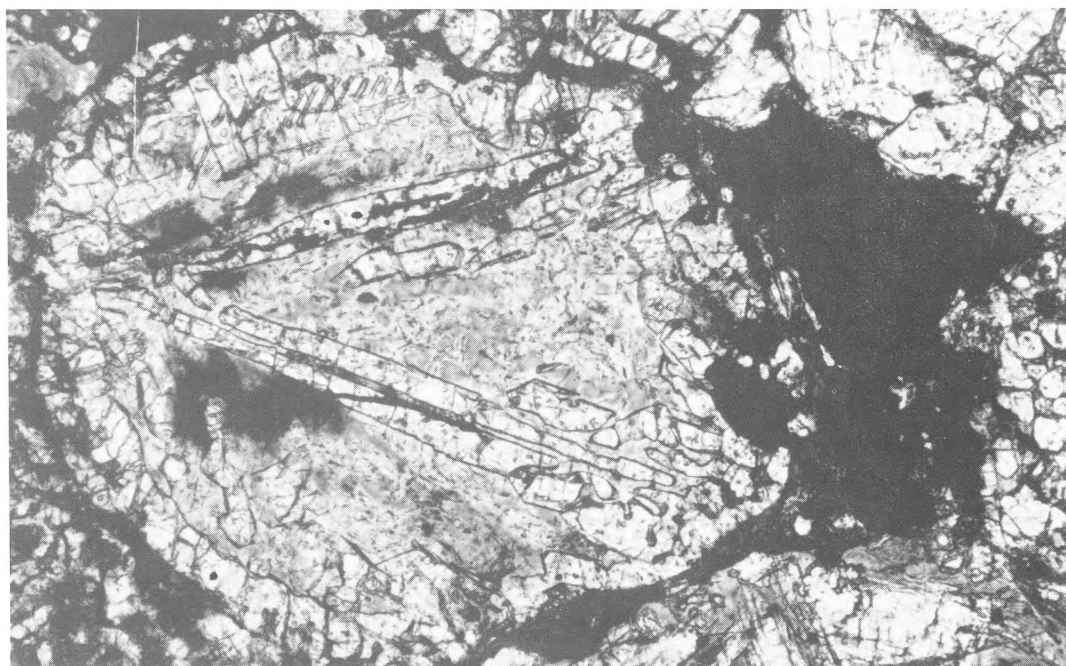
*Fig. 4.* Kediri overview in plane transmitted light, field of view 5.4 mm. Olivine porphyritic and low Ca pyroxene chondrules are most abundant with only little matrix, one chondrule in the lower left hand corner has a dark rim consisting partly of minute metal and grains; next to it is a compound pyroxene chondrule.

gonal textures and are probably lithic fragments, although some contain intergranular glass, and most show some oblateness. A few low-Ca pyroxene excentroradial chondrules have pitted surfaces suggesting collision in space between rigid objects (Figure 5). Fluid droplet chondrules vary in diameter from 0.2–3 mm and display the common internal textures ie. porphyritic, barred olivine and radiating pyroxene. There is no mineralogical evidence for shock except for undulose extinction in some relict (see below) olivine grains. Therefore Kediri could be classified as unshocked, facies ‘a’ (Dodd & Jarosewich 1979) although there is evidence for brittle fracturing and partial infilling of the cracks with troilite probably caused by a late impact event. Some fine examples of barred olivine chondrules occur, containing clear isotropic glass (Figure 6). Spinifex and herringbone (Figure 7a) quench textures testify to rapid cooling and to insignificant metamorphic crystallisation in some chondrules. Most of the low Ca pyroxene is mono-

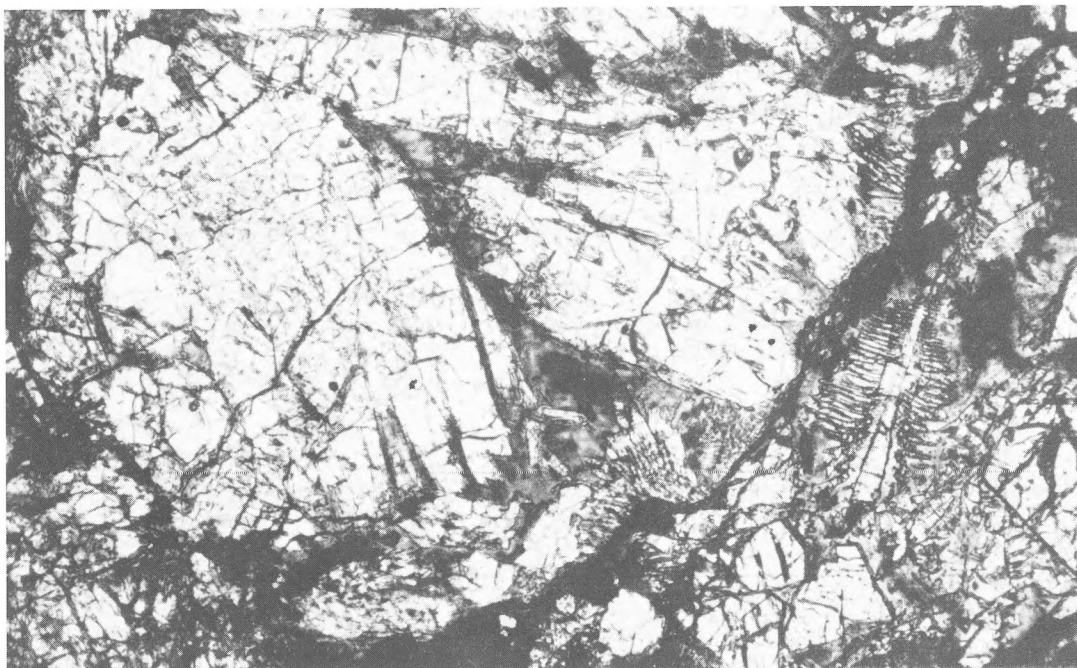
clinic, twinned, ‘quench’ pyroxene, and is only locally partially annealed to orthorhombic pyroxene. Few low Ca pyroxene grains have thin diopside rims. In some chondrules undulose olivine grains with lobate outline occur which are embedded in quench clinopyroxene (Figure 7a, b) and are presumably older than the pyroxene, although electron microprobe analyses do not show chemical disequilibrium zonation (Table 2) as described by Rambaldi (1981). Whether these relict olivine grains survived because the temperature did not reach melting point or because of kinetic effects, however, is unclear. Metal and troilite generally occur in clumps where polygonally crystallised kamacite or, more rarely, taenite grains occupy the central parts with polygonal troilite on the outside.



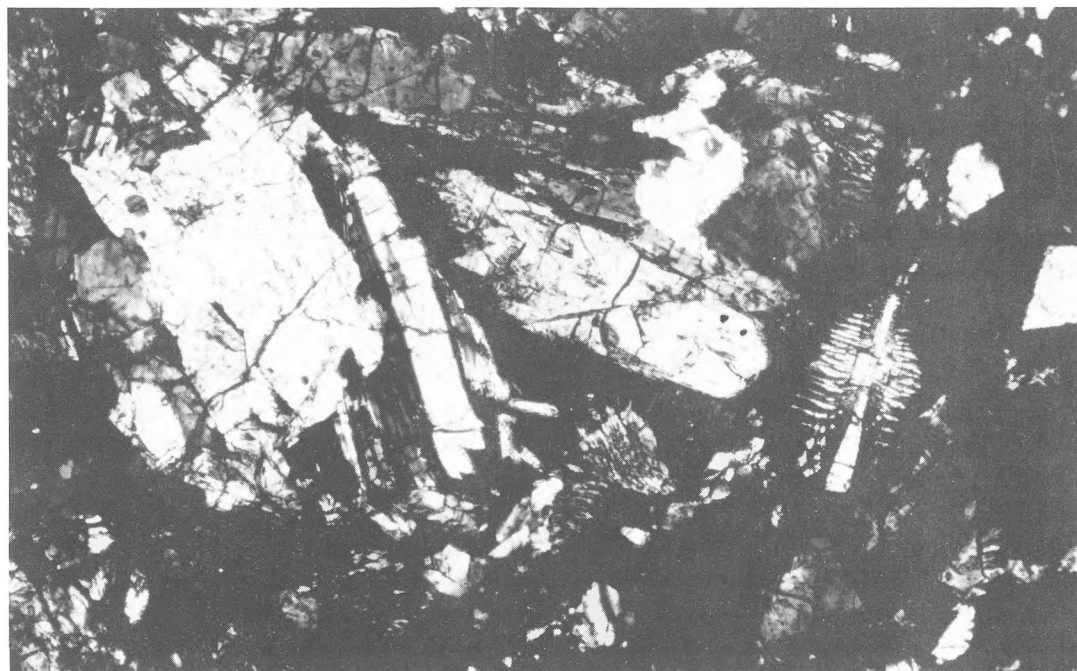
*Fig. 5.* Pyroxene chondrule in Kediri, plane transmitted light. Most of this chondrule consists of grey excentroradial pyroxene with a few white olivine grains. The pits in the surface are probably caused by collisions between rigid objects in space. Field of view 0.8 mm.



*Fig. 6.* Barred olivine chondrule with high relief olivine laths in clear isotropic glass, plane transmitted light. Note that this chondrule appears more squashed than the chondrule in Fig. 5. Field of view 0.8 mm.



*Fig. 7a.* Circa 2/3 of a single chondrule in plane transmitted light; olivine and clinopyroxene are light grey, glass is darker grey. Delicate crystals with spinifex and herringbone habits indicate rapid cooling and insignificant metamorphic equilibration; field of view 0.8 mm.



*Fig. 7b.* Same field of view in polarised light; one large lobate light grey olivine crystal in the left of the picture and a smaller one in the middle right. Twinned clinopyroxene crystals may have nucleated on the larger, undulose olivine crystal.

Table 2. Electron microprobe analyses of Kediri chondrite in thin section M1734; column 1 and 2 show analyses of individual grains while those in column 3 and 4 were made specifically to detect intra-chondrule heterogeneity, errors are one standard deviation.

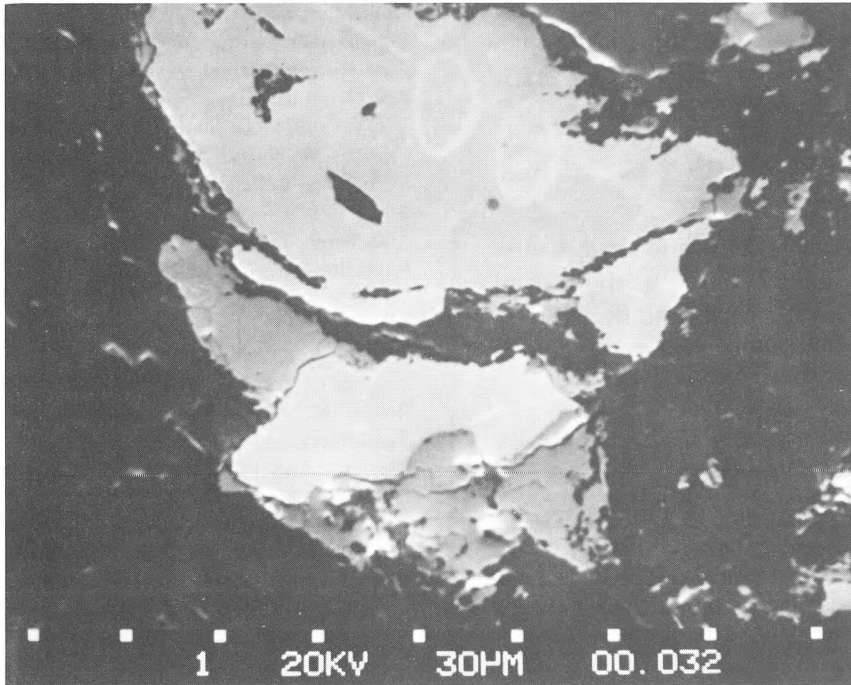
	Chondrule Fig. 7a, b														
	Olivine		Pyroxene		Olivine		Pyroxene		Glass		Kamacite		Troilite		
	1	$\sigma$	2	$\sigma$	3	$\sigma$	4	$\sigma$	5	$\sigma$	6	$\sigma$	7	$\sigma$	
SiO <sub>2</sub>	39.90	1.48	56.08	1.46	38.95	.92	54.73	.84	60.65	1.51	Fe	93.51	.32	62.56	.29
TiO <sub>2</sub>	.04	.02	.06	.03	.02	.01	.03	.01	.32	.04	Ni	5.98	.27	.1	
Al <sub>2</sub> O <sub>3</sub>	.18	.40	.63	.68	.03	.05	.13	.06	9.28	1.31	S			35.56	.23
FeO	18.67	2.70	11.65	3.24	19.21	.36	13.65	.51	6.62	1.95					
MnO	.42	.08	.46	.15	.44	.02	.55	.04	.31	.08					
MgO	41.03	3.02	29.90	3.31	40.83	.67	28.95	.70	10.72	1.16					
CaO	.19	.30	.83	.80	.06	.03	.33	.12	6.73	1.11					
Na <sub>2</sub> O			.16	.17	.01	.01	.09	.03	3.88	1.56					
Cr <sub>2</sub> O <sub>3</sub>			.49	.22	.19	.05	.37	.05	.34	.16					
Total	100.43		100.26		99.74		98.83		98.85			99.49		98.12	
No. of analyses	21		14		5		5		5			4		4	

### Kediri composition

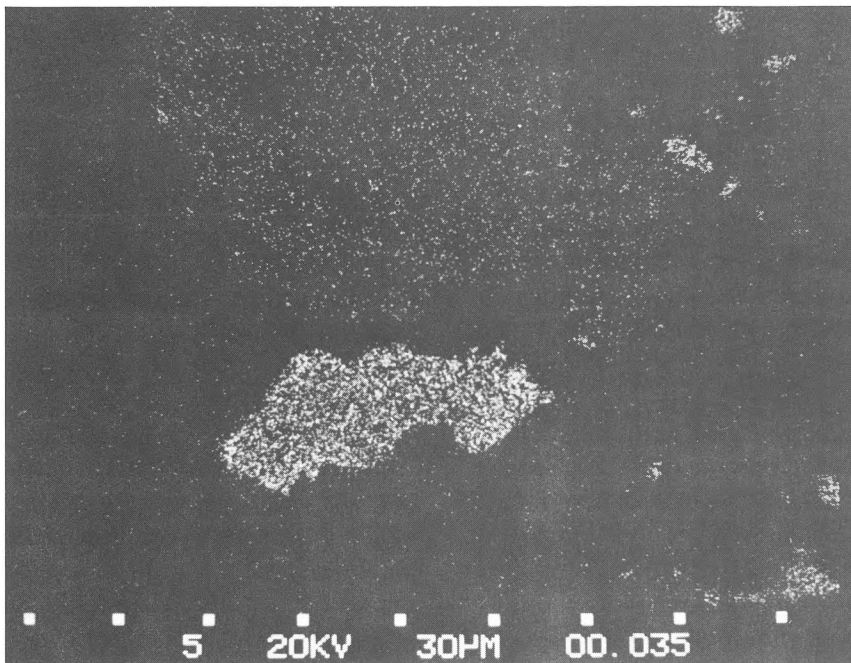
Mineral grains in Kediri were analysed with the electron microprobe using the same techniques as for the Kangean analyses. Of the 21 olivine grains analysed (Table 2) 20 yield a mean = 21.1% Fa with PMD 3.2 indicating an equilibrated L class meteorite but if the other grain with Fa 7.2 is included PMD increases to 24. Fourteen pyroxene grains were analysed (Table 2) and gave Fs = 18.2%, PMD 29. Since no whole rock analysis is available the L group classification (Meteoritical Bulletin, 1975) can only be tentatively supported. In one chondrule (Figure 7a, b), 5 electron microprobe analyses were made of both undulose relict olivine and low Ca pyroxene (Table 2) but they appear homogeneous and no complex zonation as reported for relict grains by Rambaldi (1981) was observed. Indeed these analyses are indistinguishable from the main group and show similar low CaO and Al<sub>2</sub>O<sub>3</sub> concentrations. Analyses of kamacite and troilite grains are given in table 2. Figure 8a shows a typical relation between kamacite, teanite and troilite, although kamacite is frequently the only metal phase. Figure 8b is an electron microprobe backscatter image of the Ni distribution, Ni is clearly at background level in troilite. Ni concentration in kamacite is somewhat below the canonical value of 6.5% for equilibrated chondrites but

not as low or as variable as in the least equilibrated type-3 chondrites (Rambaldi & Wasson 1984).

A mean analysis of chondrule glasses is given in table 2, it appears to be rather heterogeneous although the error on the Na<sub>2</sub>O value is magnified by the evaporation of Na under the electron beam. The average glass has high SiO<sub>2</sub> (> 60%) and MgO (> 10%) and low Al<sub>2</sub>O<sub>3</sub> and Na<sub>2</sub>O with a Mg number of 74. Such a melt is not too dissimilar from boninites (Cameron et al. 1979), especially those from Cape Vogel, Papua New Guinea, where the microphenocryst pyroxenes, presumably in equilibrium with the liquid, have Fs comparable to low Ca pyroxene in Kediri. However, olivine in Kediri is too iron rich to be in equilibrium with a liquid with Mg = 74 (Roeder & Emslie 1970). In the chondrule in Figure 7 the low Ca pyroxene probably nucleated on olivine grains. The composition of the glass is consistent with derivation by extensive low pressure fractionation of a primitive precursor. Further analysis of glass, both inside and outside the chondrules is in progress. Olivine in Kediri is equilibrated but low Ca clinopyroxene is not and the survival of delicate quench textures and probably relict olivine grains does not support a type 4 classification. The crystallinity of the matrix is difficult to assess because of its rarity and usually glassy nature. However, rare chondrules have a black rim which is not crystallized enough to



*Fig. 8a.* Opaque grain in plane reflected light. Large light grey grain in the top half of the picture is kamacite; darker grey troilite largely encompasses a white taenite grain; silicate matrix is dark grey; field of view .03 mm.



*Fig. 8b.* Ni backscatter image of the same field as Figure 8a. Ni-rich taenite grains show the highest density of white dots, kamacite is intermediate, while troilite shows no higher Ni concentration than the matrix.

lose its opacity within a very thin ( $10\ \mu\text{m}$ ) section (Figure 1). Taking into account the ambiguity in the olivine Fa variation, Kediri is best classified as L3a.

### Acknowledgements

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