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# A FELDSPAR-NEPHELINE ACHONDRITE CLAST IN PARNALLEE

John C. BRIDGES[1], Robert HUTCHISON[1], Ian A. FRANCHI[2], C. M. O'D. ALEXANDER[3]* and Colin T. PILLINGER[2]

[1]*Department of Mineralogy, Natural History Museum, Cromwell Road, London SW7 5BD, U. K.*
[2]*Department of Earth Sciences, Open University, Milton Keynes MK7 6AA, U. K.*
[3]*McDonnell Center for the Space Sciences, Washington University, St Louis, MO 63130, U. S. A.*

***Abstract:*** A feldspar-nepheline clast (FELINE) has been identified in Parnallee (LL3.6). Plagioclase is $An_{83-87}$, $Ab_{17-13}$ and nepheline contains 0.24–3.12 wt% Cl. The calculated bulk composition is mildly alkaline, with 3.5 wt% $Na_2O$. Plagioclase has heavy REE depletion and a positive Eu anomaly (Eu/Eu*=65). Nepheline has lower total REE than plagioclase. On a three isotope plot, the oxygen isotope composition of FELINE falls near the Carbonaceous Chondrites Anyhdrous Minerals Line, beneath the Terrestrial Fractionation Line. This suggests that the parental material had carbonaceous chondrite affinities. It was derived from a melt with moderately enriched LREE and Eu (13.5×CI), which probably underwent an influx of Na-, Cl-rich fluids during crystallisation. This LREE-enrichment suggests that Ca-pyroxene crystallised in the parent body residue during a melt extraction event. REE abundances and the oxygen isotope signature are consistent with an origin as a lost plagiophile melt fraction complementary to the ureilites. FELINE provides further evidence that achondritic fragments with an igneous, exotic origin are an important component of chondritic meteorites.

## 1. Introduction: Achondrite Clasts in Chondrites

An increasing number of petrographic and isotopic studies have shown that igneous clasts are a significant component of chondrites. One example is a microgabbro clast in Parnallee (KENNEDY *et al.*, 1992). The clast is 2 mm in width, has an ophitic texture and is believed to have been formed through partial melting processes in a parent body. Similarly, a 2.4 mm basaltic fragment (SA-1) was identified in Allende which has mineralogical affinities with eucrites and lunar basalts (KENNEDY and HUTCHEON, 1992). SA-1 records a complex history with mixing of both igneous differentiates and nebular material before final melting and crystallisation. Granitoidal clasts containing K-rich feldspar, silica polymorphs and ilmenite have been identified in the Adzhi-Bogdo LL3-6 chondritic breccia (BISCHOFF *et al.*, 1993). These clasts were believed to have formed from the final fraction of crystallising melt in achondritic planetismals. Oxygen isotopic studies have also demonstrated the presence in many ordinary chondrites of xenoliths from different chemical groups and other meteorite classes (*e.g.* CLAYTON *et al.*, 1991).

*Current address: Department of Terrestrial Magnetism, The Carnegie Institute of Washington, 5241 Broad Branch Road, Washington, D.C. 20015, U.S.A.

Achondritic clasts in chondrites clearly have a variety of origins. Oxygen isotope and trace element analyses can help illuminate their relationships to other meteorite groups and give information about their petrogenesis. The small sample sizes now required for oxygen isotope analysis also increase the number and variety of clasts that can be studied. Here we describe a feldspar-nepheline clast (FELINE) in Parnallee (LL3.6) and discuss its possible origins.

## 2. Techniques

FELINE was separated from a broken surface of Parnallee (BM 34792). Two polished thin sections of different parts of the clast were made and approximately 1mg was taken for oxygen isotope analysis. Major element mineral analyses were made with a Cameca SX50 wavelength dispersive microprobe at an accelerating voltage of 20 kV and probe current of 20 nA. A PAP correction procedure was used for these. Oxygen isotope analyses (FRANCHI *et al.*, 1992) were made by heating the sample with a defocussed $CO_2$ laser beam (25W, 10.6 $\mu$m radiation) in the presence of 0.1 atm $ClF_3$ for 2–3 min. Following purification the oxygen was analysed on a dual inlet, dynamic mass spectrometer (Dennis Leigh Technology Ltd, U.K.). REE and other trace element analyses were performed on a polished section of FELINE with the Washington University Cameca IMS 3f ion microprobe using a 12 kV $O^-$ primary beam, positive secondary ions and energy filtering. The elemental abundances were obtained from the secondary ion intensities at various masses using a modification (ALEXANDER, 1994) of the method outlined by ZINNER and CROZAZ (1986).

## 3. Feldspar-Nepheline Clast (FELINE)

FELINE is a 3 mm diameter subrounded feldspar-nepheline clast (Fig. 1) consisting of 88 modal% plagioclase and 12 modal% nepheline (Fig. 2). There is no mesostasis and the only other minor phase identified is troilite which is found as veins

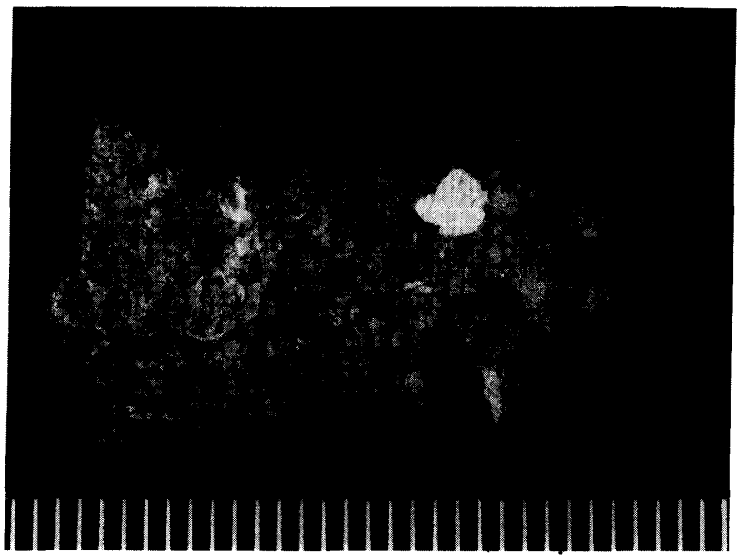

*Fig. 1. The clast exposed on a broken surface of Parnallee. Scale in mm.*

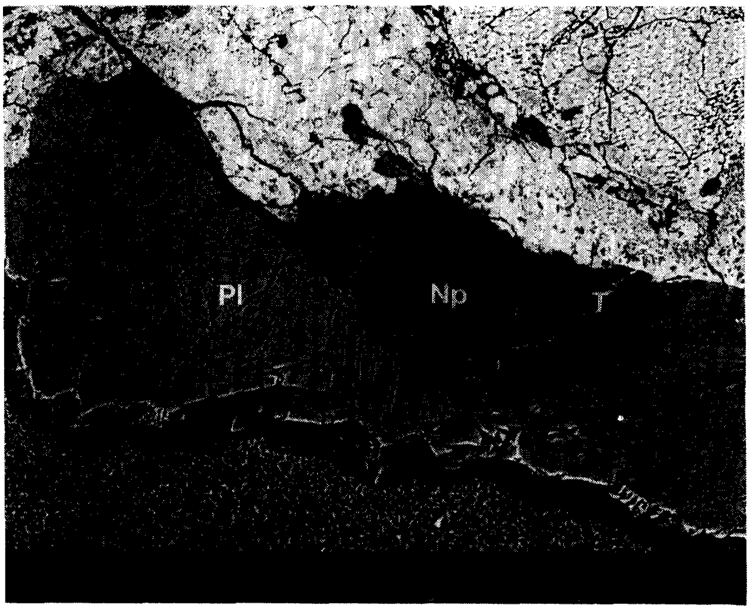


*Fig. 2. Back-scattered electron image of plagioclase (Pl) and nepheline (Np) in FELINE and the contact with surrounding Parnallee matrix. Minor troilite (T) veining is present in the clast. Cracks are seen to be continuous between the clast and the surrounding matrix suggesting post accretion fracturing.*

in a fractured area linked to the Parnallee matrix. The extension of fractures from FELINE into the surrounding matrix shows that the clast has undergone minor post-accretion fracturing in the Parnallee parent body. Prior to this late event the plagioclase appears to have consisted of only a few individual crystals. The apparently truncated margin of the plagioclase and nepheline grains suggests that FELINE is a fragment of a larger body. There is neither chilled margin nor fine-grained rim that typically encloses chondrules. The interlocking texture of the plagioclase and nepheline is consistent with co-crystallisation of the two phases.

## 4. Mineral Compositions and REE Abundances

Plagioclase has a uniform composition of $An_{83-87}$, $Ab_{17-13}$ with <0.03 wt% $K_2O$ (Table 1), apart from one isolated analysis point which is $An_{75}$, $Ab_{25}$. Nepheline contains variable Cl contents, within a range of 0.24–3.12 wt%. The bulk composition of FELINE (Table 1) has been calculated using the average compositions and modal abundances of the plagioclase and nepheline. This mildly alkaline composition, with

*Table 1. Mineral analyses and bulk composition of FELINE.*

| | $SiO_2$ | $Al_2O_3$ | $TiO_2$ | FeO | MgO | MnO | $K_2O$ | CaO | $P_2O_5$ | $Cr_2O_3$ | $Na_2O$ | Cl | Total | An | Ab | Or |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Plag. | 45.71 | 33.33 | 0.05 | 0.11 | 0.09 | 0.00 | 0.00 | 17.66 | 0.00 | 0.00 | 1.67 | 0.00 | 98.62 | 0.85 | 0.15 | 0.00 |
| | 45.75 | 34.06 | 0.02 | 0.04 | 0.09 | 0.04 | 0.00 | 17.87 | 0.04 | 0.00 | 1.45 | 0.01 | 99.37 | 0.87 | 0.13 | 0.00 |
| | 46.46 | 33.33 | 0.06 | 0.10 | 0.10 | 0.00 | 0.02 | 17.07 | 0.05 | 0.00 | 1.87 | 0.00 | 99.06 | 0.83 | 0.17 | 0.00 |
| Neph. | 44.56 | 33.43 | 0.04 | 0.18 | 0.00 | 0.00 | 0.01 | 0.24 | 0.00 | 0.04 | 21.00 | 0.27 | 99.77 | | | |
| | 44.92 | 33.63 | 0.03 | 0.20 | 0.00 | 0.04 | 0.05 | 1.29 | 0.03 | 0.02 | 19.47 | 0.24 | 99.92 | | | |
| | 45.57 | 34.60 | 0.02 | 0.11 | 0.04 | 0.01 | 0.44 | 0.66 | 0.01 | 0.03 | 16.90 | 1.64 | 100.03 | | | |
| Bulk | 45.12 | 33.17 | 0.03 | 0.06 | 0.04 | 0.01 | 0.06 | 15.38 | 0.01 | 0.01 | 3.52 | 0.22 | 97.63 | | | |

Plag. plagioclase, Neph. nepheline.

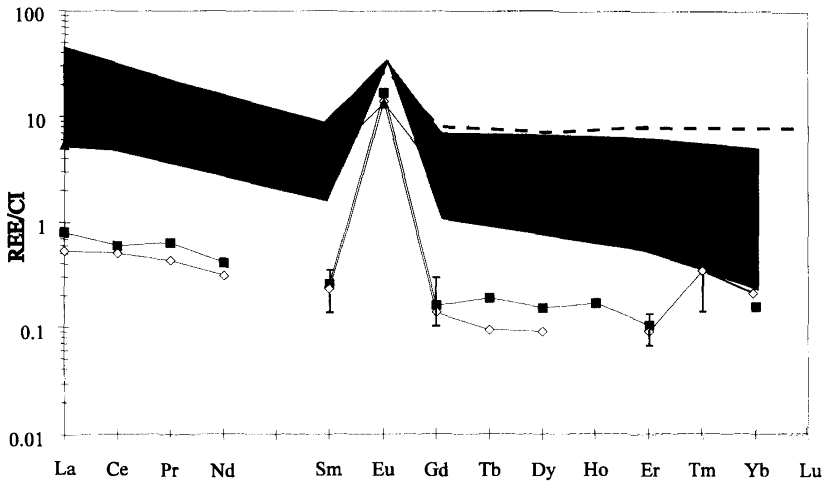


*Fig. 3. The CI normalised REE abundances of the plagioclase in FELINE (two analyses, Plag.6.N plotted with squares and Plag.1.N diamonds) and the calculated melt from which the plagioclase was derived (triangles). The shaded area contains the range of REE abundances in the plagioclase of a Parnallee microgabbro fragment (KENNEDY et al., 1992) and the dashed line is the upper limit of REE abundances in the plagioclase of Allende basaltic clast SA-1 (KENNEDY and HUTCHEON, 1992). Some of the larger 1 sigma error bars for the FELINE plagioclase analyses are shown. CI abundances from ANDERS and GREVESSE (1989).*

3.5 wt% $Na_2O$, is distinct from Al-rich chondrules (BISCHOFF and KEIL, 1984) in having no significant contents of MgO and FeO.

The plagioclase has total REE contents of between 0.1 and 1 times CI chondrite apart from Eu which has 14 to 16 times the CI values. The CI-normalised slope is negative with Eu/Eu*=65 (Fig. 3, Table 2). Eu* is the abundance of Eu extrapolated between Sm and Gd. The nepheline has similar REE profiles to the plagioclase with positive Eu anomalies but lower total REE (0.01–0.1 times CI, Fig. 4). Nepheline has higher abundances of the Large Ionic Lithophile elements (LILE) Rb, Zr, Nb and Cs (Table 2). REE abundances of plagioclase in the Allende SA1 basaltic clast (KENNEDY and HUTCHEON, 1992) and the Parnallee microgabbro clast (KENNEDY *et al.*, 1992) are shown for comparison.

## 5. Oxygen Isotopes

The oxygen isotope composition of FELINE is $\delta^{17}O=+4.5‰$, $\delta^{18}O=+8.9‰$. FELINE lies away from the ordinary chondrite field on the three isotope plot (Fig. 5) showing its exotic origin relative to most of the chondrules and clasts in Parnallee. It plots just below the intersection of the Carbonaceous Chondrite Anhydrous Minerals Line (CCAM) with the Terrestrial Fractionation Line (TFL) suggesting a broad grouping with carbonaceous chondrites. The ureilite group of achondrites (CLAYTON and MAYEDA, 1988) also plot along CCAM but do not quite extend up to the FELINE composition. FELINE overlaps the CR (Renazzo-type) whole rock chondrite and

*Table 2. REE and trace element analyses.*

| | Ne.20.N | Ne.15.N | Ne.16.N | Plag.6.N | Plag.1.N | | |
|---|---|---|---|---|---|---|---|
| Rb | 1.9(0.6) | 2.1(0.1) | 4(0.4) | 0.13(0.02) | 0.22(0.03) | | |
| Sr | 21.4(0.5) | 6.8(0.4) | 25.3(1.2) | 261.7(1.9) | 181.9(2.3) | | |
| Y | 0.081(0.006) | 0.07(0.01) | 0.23(0.02) | 0.17(0.01) | 0.1(0.01) | | |
| Zr | 0.15(0.01) | 0.08(0.01) | 0.088(0.009) | 0.030(0.005) | 0.044(0.005) | | |
| Nb | 0.066(0.008) | 0.01(0.003) | 0.03(0.005) | <0.005 | 0.003(0.002) | | |
| Cs | 0.7(0.1) | 0.9(0.1) | 0.9(0.1) | 0.55(0.04) | 1.1(0.1) | | |
| Ba | 1.6(0.1) | 0.8(0.1) | 2.3(0.2) | 13.7(0.5) | 5.4(0.3) | | |
| | | | | | | Kd | Melt |
| La | 0.16(0.02) | 0.09(0.02) | 0.19(0.03) | 0.19(0.02) | 0.13(0.02) | 0.14 | 1.36 |
| Ce | 0.29(0.03) | 0.17(0.03) | 0.40(0.05) | 0.36(0.06) | 0.31(0.03) | 0.107 | 3.360 |
| Pr | 0.031(0.003) | 0.015(0.004) | 0.042(0.006) | 0.057(0.007) | 0.039(0.007) | | |
| Nd | 0.13(0.01) | 0.049(0.007) | 0.17(0.01) | 0.19(0.02) | 0.14(0.02) | 0.094 | 2.020 |
| Sm | <0.002 | 0.008(0.006) | 0.028(0.008) | 0.04(0.01) | 0.03(0.01) | 0.0588 | 0.68 |
| Eu | 0.046(0.005) | 0.013(0.002) | 0.065(0.006) | 0.95(0.06) | 0.79(0.04) | 1.2 | 0.80 |
| Gd | 0.018(0.008) | 0.005(0.002) | 0.06(0.01) | 0.03(0.01) | 0.028(0.009) | 0.049 | 0.61 |
| Tb | <0.0005 | <0.002 | 0.004(0.002) | 0.007(0.001) | 0.004(0.002) | | |
| Dy | 0.006(0.004) | 0.007(0.003) | 0.047(0.006) | 0.038(0.006) | 0.023(0.005) | 0.0495 | 0.768 |
| Ho | 0.003 | 0.002(0.001) | 0.014(0.003) | 0.010(0.002) | 0.002(0.001) | | |
| Er | 0.007(0.003) | 0.006(0.002) | 0.018(0.004) | 0.017(0.005) | 0.015(0.005) | 0.0439 | 0.387 |
| Tm | <0.001 | <0.001 | 0.002(0.001) | 0.007(0.004) | 0.009(0.006) | | |
| Yb | 0.011(0.004) | 0.005(0.003) | 0.028(0.006) | 0.026(0.007) | 0.040(0.008) | | |
| Lu | <0.006 | <0.001 | <0.004 | <0.001 | <0.002 | | |

Concentrations in ppm with 1 sigma errors in brackets. Sample identifiers Ne.20.N, Ne.15.N, Ne.16.N nepheline analyses; Plag.6.N, Plag.1.N plagioclase analyses. The melt composition was calculated from Plag.6.N using distribution coefficients (Kd) from DRAKE and WEILL (1975). Eu Kd from DRAKE (1975).

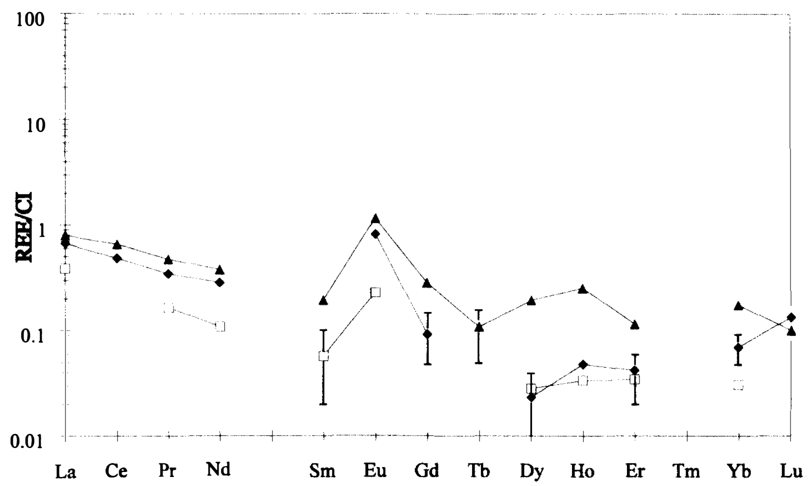


*Fig. 4. The CI normalised REE abundances in the nepheline of FELINE (three analyses; triangles Ne.16.N, diamonds Ne.20.N, squares Ne.15.N). Some of the larger 1 sigma error bars are shown. CI abundances from ANDERS and GREVESSE (1989).*

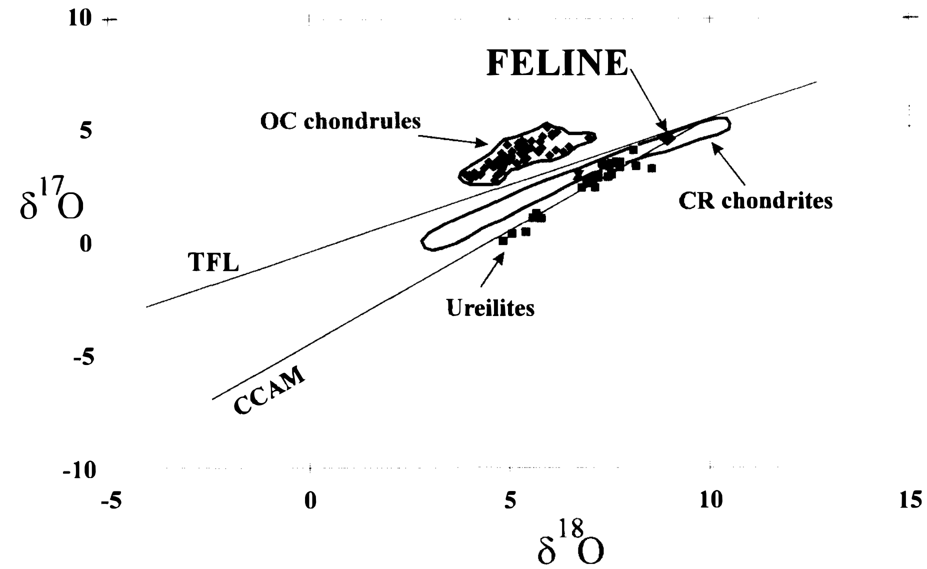


*Fig. 5.* *Oxygen three isotope plot relative to SMOW. FELINE is $\delta^{17}O=+4.5‰$, $\delta^{18}O=+8.9‰$ and lies close to the Carbonaceous Chondrite Anhydrous Minerals Line (CCAM), beneath the Terrestrial Fractionation Line (TFL). Also plotted are the fields of ordinary chondrite chondrules (*CLAYTON *et al., 1991), ureilites and a plagioclase-rich clast (x) from the Nilpena ureilite breccia (*CLAYTON *and* MAYEDA*, 1988), and CR chondrites (*WEISBERG *et al., 1993).*

chondrules field, which lies on a slope 0.7 mixing line (WEISBERG *et al.*, 1993). A plagioclase-rich clast from the Nilpena ureilite breccia (CLAYTON and MAYEDA, 1988) lies within the ureilite field (Fig. 5).

## 6. Discussion

Although the bulk composition of FELINE is alkaline, the mineralogy is not consistent with an origin through crystallisation from a highly fractionated residual melt as, for instance, is believed to be the case for the granitoidal clasts of Adzhi-Bogdo (BISCHOFF *et al.*, 1993). Those clasts contained feldspar that is more K-rich than in FELINE as well as silica polymorphs and ilmenite. Plagioclase from the Allende SA1 basaltic clast (Fig. 3) has from <1 to 18 times CI total REE concentrations (KENNEDY and HUTCHEON, 1992) and the Parnallee microgabbro clast plagioclase has between 4 and 50 times CI concentrations of La (KENNEDY *et al.*, 1992). Plagioclase in FELINE does not contain such enrichment of REE. The nepheline in FELINE has lower REE abundances than the plagioclase but similar CI normalised profiles. This is consistent with the similar or lower REE partition coefficients for nepheline compared to plagioclase in alkaline melts (ONUMA *et al.*, 1981). This together with the textures in FELINE suggests that the nepheline and plagioclase crystallised at the same time. Co-crystallisation is also preferred to the formation of nepheline by late parent body alteration of plagioclase because the nepheline crystallised before the fracturing and minor troilite veining which are clearly parent body effects. A similar conclusion was reached by HUTCHISON *et al.*

(1994) for most co-existing nepheline and plagioclase in the mesostasis of a Parnallee chondrule. There is, however, insufficient evidence to rule out entirely the possibility that the nepheline formed by alteration on the FELINE parent body prior to accretion into the Parnallee parent body.

Clasts and chondrules with diverse origins in chondrites have experienced a widespread flux of Na-, Cl-rich fluids from unknown extraneous sources. An example of this may be found in the SA-1 basaltic clast of Allende, which underwent an influx of Na at a late stage in anorthite crystallisation (KENNEDY and HUTCHEON, 1992). The Na content of FELINE which has an overall nepheline normative composition, may well be the result of a Na- and Cl- rich fluid influx into the melt. The Na-, Cl-rich fluids in some chondrites proved to have had little or no influence on REE mobility (HUTCHISON *et al.*, 1994).

Approximate REE abundances of the melt from which the FELINE plagioclase crystallised have been calculated (Table 2, Fig. 3). The melt is moderately light REE (LREE) enriched with between 5.4 and 4.3 times CI for La to Nd. There is also a Eu anomaly in the calculated melt of 13.5 times C1 and Eu/Eu*=9.8. Partition coefficients, apart from Eu, were taken for plagioclase-melt in basaltic systems (DRAKE and WEILL, 1975). The Eu distribution coefficient was taken for $fO_2$ of $\log_{10}^{-12.5}$ and at a temperature of 1290°C (DRAKE, 1975).

A carbonaceous chondrite-related source for the parental melt is consistent with the oxygen isotopic signature of FELINE. Although the oxygen isotope composition of FELINE overlaps the range of oxygen isotopes from CR chondrites, there is no mineralogical reason to suggest a genetic link with that particular meteorite class. The moderately LREE-enriched melt from which the plagioclase is inferred to have crystallised suggests prior crystallisation and loss of Ca-pyroxene from the melt (*e.g.*, KENNEDY *et al.*, 1992). FELINE possibly is a fragment of a pyroxene-bearing rock, but we prefer the alternative explanation of Ca-pyroxene crystallising out as a residue during the melt extraction from carbonaceous chondrite material. This can explain the positive Eu anomaly of the calculated melt. Experimental evidence indicates that Ca-pyroxene in equilibrium with melt at oxygen fugacities, ($fO_2=10^{-13.1}-10^{-13.5}$), similar to those at which the plagioclase Eu distribution coefficient was calculated, has negative Eu anomalies (Fig. 3 in CONSOLMAGNO and DRAKE, 1977) which would lead to positive anomalies in the separated melt. This in turn suggests a possible link with the ureilites.

*Possible links with ureilites*

The genesis of ureilites is still under discussion, with igneous models requiring extensive planetary differentiation or primitive models involving relatively limited reworking and melting of primitive precursors (GOODRICH, 1992). It is believed that the ureilites are derived from carbonaceous chondrite-like material because of their position near CCAM on the oxygen three isotope plot (CLAYTON and MAYEDA, 1988). Another factor common to all models of ureilite genesis is the requirement for loss of a plagiophile element-rich, basaltic melt as the meteorites are predominantly composed of olivine and pigeonite. TOMEOKA and TAKEDA (1990) suggested that plagiophile elements were lost from ureilite parent bodies along veins or fissures during impact events. Plagioclase-bearing clasts have been identified in ureilite breccias (PRINZ *et al.*, 1988; CLAYTON and MAYEDA, 1988) and some may represent products of this lost fraction. The clasts are dominated by the feldspathic component but unlike FELINE, this is $An_{10-50}$ and some low-Ca pyroxene or olivine is also present. The REE contents of plagioclase from ureilite breccias and FELINE are similar. A feldspathic clast and two isolated plagioclase grains in the North Haig polymict ureilite were found to have REE below CI levels, apart from Eu which ranged in abundance from 8 to 22 times CI (DAVIS *et al.*, 1988).

## 7. Conclusions

The plagioclase in FELINE crystallised from a melt with slightly enriched LREE probably due to prior crystallisation of Ca-pyroxene. At a late stage in the crystallisation there is believed to have been an influx of Na-, Cl-rich fluids. This gave rise to the crystallisation of Cl-rich nepheline and gave the mineral assemblage its alkaline composition.

FELINE is different from other achondrite, igneous clasts found in chondrites because it does not have the large degree of REE enrichment characteristic of derivation from a highly differentiated melt. The oxygen isotope ratios suggest that the parental source had carbonaceous chondrite affinities. Other than this broad isotopic affinity it is not certain that FELINE has any links with other meteorite groups. One possibility is that FELINE is part of the missing feldspathic component from ureilites. Such a relationship is consistent with the oxygen isotope signature of FELINE, the REE contents of the plagioclase and the REE abundances of the calculated parental melt which imply the presence of a Ca-pyroxene rich residue.

This study is part of an increasing body of work which shows that achondritic clasts with an igneous origin are an important component of chondrites. FELINE also provides more evidence that ordinary chondrites preserve a record of mixing between diverse meteorite types.

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