

ZAG (b): A FERROAN ACHONDRITE INTERMEDIATE BETWEEN BRACHINITES AND LODRANITES. J. S. Delaney¹, B. Zanda^{1,2}, R. N. Clayton³ and T. Mayeda³, ¹Department of Geological Sciences, Rutgers University, Piscataway, NJ08854 (jsd@rci.rutgers.edu); ²MNHN/CNRS-ESA7058, 61, rue Buffon – 75005 - Paris, France; ³Univ. Chicago, E.Fermi Inst., Chicago, IL60637.

Introduction: We report here on a new achondrite which was found in 1999 very close to the site of Zag and which we call Zag (b) hereafter. The name is provisional and remains to be approved. Zag (b) consists of a single 300g well oriented achondritic stone, olivine-rich and unbrecciated. Examination of a sawn surface reveals sub-centimeter regions in which the modal contents of olivine and (ortho)pyroxene vary tremendously. One of the most striking features of Zag (b) is that most of the olivine crystals contain embedded orthopyroxene channels of a few μm width, containing angular metal (or sulfide or weathered metal) grains which appear to be the product of a reduction reaction. Oxygen isotopes for Zag (b) ($\delta^{18}\text{O}=+4.84$, $\delta^{17}\text{O}=+2.06$) place it very close to Divnoe [1], within the winonaite-IAB range and on the outskirts of the brachinite range. The olivine and pyroxene compositions place it close to Divnoe and the brachinites, and it is this relationship which is explored below. A connection with the winonaite will be explored later.

Petrography: Modal analyses of a single (hopefully representative) polished section yielded: olivine (68% vol), orthopyroxene (8%), clinopyroxene (10%), chromite(<1%), phosphate(<1%), metal (1.5%) and sulfide/weathered metal (12%). Olivine composition in Zag (b) is relatively homogeneous and is more magnesian (Fo78) than that in Divnoe and Brachina (Table 1, Figure 1). Modal data are not given for Divnoe as the sections studied are small and possibly unrepresentative ([2]; M. Prinz, pers. comm.)

Both orthopyroxene and clinopyroxene in Zag (b), Divnoe and even in Brachina have similar compositions particularly with respect to Fe-Mn-Mg variations (Figure 2). Only the orthopyroxene inclusions in Zag (b) olivine differ significantly as they are less calcic and more magnesian having Fe/Mg ratios comparable to the olivine in which they are found. The inclusion opx is not at equilibrium with the other pyroxene in these rocks but may be equilibrated with the host olivine. Given the abundance of metal and sulfide also present in the olivine, the opx presumably represents a product of reduction of more Fe-rich olivine according to a reaction such as $\text{Fe}_2\text{SiO}_4 + \text{CO} = \text{Fe} + \text{FeSiO}_3 + \text{CO}_2$, that results in remaining olivine becoming more magnesian. The initial composition of the olivine was conceivably similar to that in Divnoe or even Brachina and was in equilibrium with both Fe-rich

ortho- and clinopyroxene. The Fe-Mn-Mg systematics for both pyroxene and olivine are consistent with such a reaction (Figure 1 and 2). This reaction is the reverse of the direction proposed by Nehru et al (1992) for the production of brachinites, but the textural setting in Zag (b) is most consistent with reduction of olivine rather than oxidation.

Table 1

	Zag (b)				Divnoe		
	Oliv.	Opx in Ol.	Opx	Cpx	Oliv	Opx	Cpx
SiO ₂	38.33	55.70	53.71	53.02	36.86	53.98	52.39
TiO ₂	0	0.12	0.28	0.60	0.02	0.11	0.09
Al ₂ O ₃	0.03	0.04	0.11	0.15	0	0.45	0.76
Cr ₂ O ₃	0.03	0.35	0.18	0.71	0.02	0.17	0.56
FeO	18.85	11.93	16.33	6.73	24.15	14.7	6.67
MnO	0.54	0.49	0.42	0.26	0.46	0.45	0.25
MgO	42.29	30.10	25.55	15.74	38.35	27.06	16.17
CaO	0.07	0.52	1.15	21.09	0.04	1.56	21.9
Total	100.1	99.25	97.73	98.30	99.9	98.48	98.79
Fo/En	80.00	80.9	71.9	45.1	73.9	74.28	45.36
Wo		1.0	2.3	43.8		3.08	44.15
Fe/Mn	35.00	24.0	38	28	52	32.25	26.34

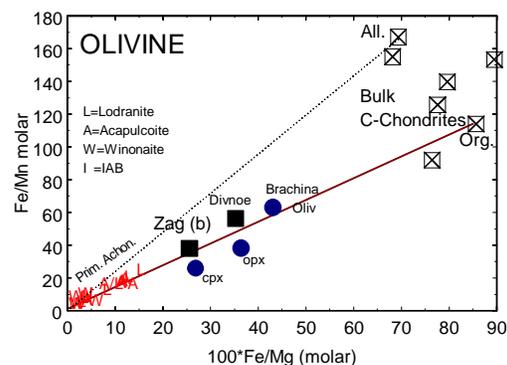


Figure 1: Fe-Mn-Mg diagram for olivine in Zag (b), Divnoe, brachinites and primitive achondrite groups.

Discussion: Olivine, the dominant mineral in Zag (b), Divnoe, and Brachina, varies from the Fo80 of Zag (b) through Fo74 in Divnoe, to Fo70 in Brachina. If these achondrites were related by conventional magmatic processes, Zag (b) should be the most primitive meteorite while Brachina is the most evolved. However, crystal-liquid partitioning data for Fe-Mn-Mg exchange implies little or no change in

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Fe/Mn (molar) with increasing Fe whereas the observed data show increasing Fe/Mn as Fe/Mg increases from Zag (b) through Divnoe to Brachina[3,4]. In addition, the textural relationships between the olivine and orthopyroxene inclusions and metal +/- sulfide imply a redox exchange process.

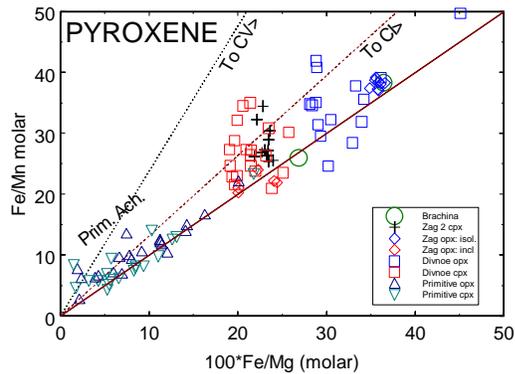


Figure 2: Detail of Fe-Mn-Mg diagram for pyroxene in Zag (b), Divnoe, brachinites and primitive achondrites.

If the reduction of Fe-olivine in Zag (b) reflects a more general process, then Zag (b) may be the end product of a reduction process that began with a precursor resembling Divnoe or perhaps even a brachinite. Reduction (by CO?) precipitated Fe-metal from the olivine present to form more Mg-rich olivine and orthopyroxene. Such a reaction would reproduce the Fe-Mn-Mg relationships among the olivine and pyroxene of Zag (b), Divnoe and Brachina as shown in Figures 1 and 2.

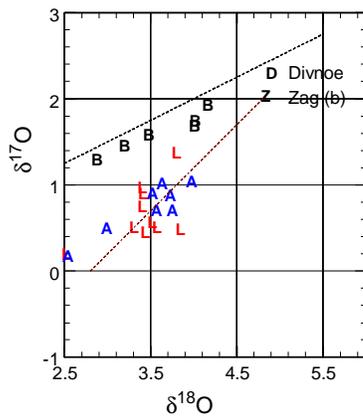


Figure 3: Oxygen in Zag(b) [Z], Divnoe [D], Brachinites [B], lodranites [L], Acapulcoites [A]

The Fe-Mn-Mg data also indicate that Zag (b) and Divnoe have chondritic Mn/Mg ratios and can be readily related to a CI nebular composition with no indication of volatile Mn depletion.

Lodranites and acapulcoites also fall on this same Fe-gain/loss trajectory from CI-compositions [5]. Although they are significantly more magnesian, these meteorites cluster about the ^{16}O mixing line passing through Zag (b) and Divnoe in oxygen isotope space. Fe-Mn-Mg relationships suggest that Zag (b) may actually be intermediate between the lodranite-acapulcoite cluster and Divnoe. Evidence of reduction processes is also commonly observed in lodranites which show little evidence of being related to one another by mass dependent oxygen fractionation processes (Figure 3). Further hints of a reduction relationship between Divnoe, Zag (b) and the lodranites are provided by systematic $\Delta^{17}\text{O}$ changes with Fe/Mg. Zag (b) and Divnoe fall on the Fe-rich extension of a previously recognized correlation between $\Delta^{17}\text{O}$ and Fe/Mg [5]. This relationship is directly comparable to that seen in ureilites [6] and implies that $\Delta^{17}\text{O}$ is reflecting the extent of redox exchange between the silicate fraction of the meteorite precursor and a ^{16}O rich gas phase. ^{16}O -bearing CO provides a tempting candidate for such a gas exchange mechanism. The absolute change in $\Delta^{17}\text{O}$ seen within the lodranite - acapulcoite - Zag (b) - Divnoe - brachinite cluster is smaller than that seen in ureilites while the range of Fe/Mg and Fe/Mn changes is comparable. Since at least two distinct petrographic subclusters exist within this group of primitive achondrites, it is unlikely that the redox exchange occurred within a single parent and the variations seen represent variable nebular modification of a common chondritic precursor to all of these meteorite types.

References: [1] Clayton, Mayeda (1996) GCA, 60,1999. [2] Peteav et al. (1994) Meteoritics, 29,182; [3] Mittlefelhd et el (1998) Rev. Mineral. 36, Ch4; [4] Nehru et al. (1983) JGR,88,B237; [5] Goodrich, Delaney (2000), GCA, in press; [6] Goodrich (1997) LPSC XXVIII, 435.

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