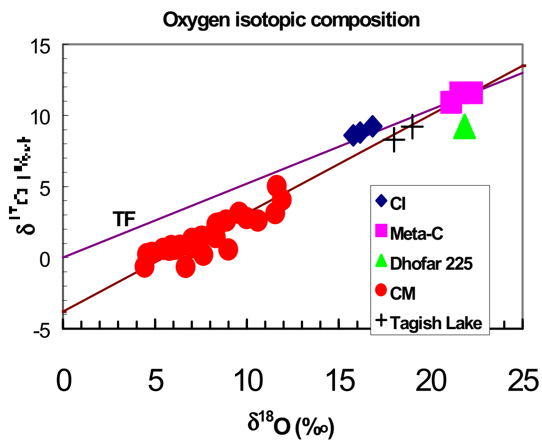
DHOFAR 225 VS. THE CM CLAN: A METAMORPHOSED OR NEW TYPE OF CARBONACEOUS CHONDRITES? Marina A. Ivanova[1], Lawrence A. Taylor[2], Robert N. Clayton[3], Toshiko K. Mayeda[3], Mikhail A. Nazarov[1], Franz Brandstaetter[4], and Gero Kurat[4]. [1]Vernadsky Institute of Russian Academy of Sciences, Kosygin St., 19, Moscow 117795, Russia (venus2@online.ru), [2]Planetary Geosciences Institute, University of Tennessee, Knoxville, TN 37996, USA; [3]Enrico Fermi Institute, Univ. of Chicago, Chicago IL 60637, [4]Natural History Museum, A-1014, Vienna, Austria.

Introduction. Dhofar 225 is similar to CM chondrites texturally and in basic mineralogy and chemistry but it has an anomalous oxygen isotopic composition, low - H_2O content, and peculiarities in chemistry, atypical for CM chondrites. Dhofar 225 contains a new mineral phase, a Ca and Fe oxysulfide, which has not been found in nature. The meteorite also contains rare phases such as eskolaite and Cr-barringerite. We report here on the petrography, mineralogy, chemistry and oxygen isotopes of Dhofar 225, and discuss its relationship with other carbonaceous chondrites.

Petrography. Dhofar 225, a 90 g carbonaceous chondrite, was found in the desert of Oman on January 15, 2001. It is a black, very fresh stone with a distinct fusion crust. Texturally it is similar to CM-chondrites. Irregular olivine aggregates, chondrule-like objects, CAIs, isolated minerals, and fragments are embedded in a fine-grained matrix. Dark fine-grained, accretional - dust mantles surround some coarse-grained objects. Rounded phyllosilicate-rich objects with opaque minerals and PCP-objects (tochilinite) also occur.

In Dhofar 225, olivine aggregates and chondrule-like olivine objects are common whereas Type I and Type II chondrules are rare. The mean chondrule diameter is around 0.3 mm, similar to that in CM meteorites [1]. The chondrules consist of olivine with minor chromite and sulfides. These phases are embedded in a completely altered phyllosilicate mesostasis. Olivine aggregates range up to 0.6 mm, - they are larger than chondrules and chondrule-like objects. CAIs of up to 220 µm in size are rare and consist of spinel, perovskite, diopside, and phylloslicates. Isolated olivine grains vary from 5 – 200 µm in size. The matrix consists mainly of phyllosilicates. Minor phases of the matrix are sulfides, phosphides, phosphates, FeNi metal, chromite, and eskolaite. There are some veins, which are composed from carbonates.

Oxygen isotopic composition of Dhofar 225 is anomalous for CM chondrites (Fig. 1). It is close to Tagish Lake carbonaceous chondrite, which has characteristics of CI and CM chondrites and resembles some metamorphosed carbonaceous chondrites such as Antarctic meteorites Belgica 7904, Yamato 82162, and Yamato 86720 [2]. These meteorites have chemical and petrographic characteristics that indicate their origin from CI or CM chondrites by metamorphism.



Mineral chemistry. There is a big compositional range of olivine in Dhofar 225. Olivine is Fo-rich in aggregates, CAIs, and Type I chondrules. In Type II chondrules olivine is Fo 35-99.5. Isolated olivine grains have compositions similar to those of other CM chondrites. Fe, Mn, and Cr, Al are positively correlated, whereas Fe and Ca are slightly negatively correlated in Fo-rich olivine. CaO and Al_2O_3 contents are as high as 1 wt.% and 0.5 wt.%, respectively in the most forsteritic olivines. In Type II chondrules olivines are strongly zoned, from Fo 97-64. There are positive correlations between FeO, MnO as well as FeO and Cr_2O_3 in the olivines.

Low-Ca pyroxenes (Wo4 En92 Fs4) are very rare in this meteorite. Rare **augite** (Wo39 En58 Fs3) occurs in chondrule-like objects, **Al-diopsides** (11.7 wt.%, Al_2O_3; 3.9 wt% TiO_2) were found in CAIs. The Al-diopsides are notably lower in MnO (0.05 wt.%) as compared to the augites (0.11 wt.%).

Secondary phases ("**spinach**") in chondrules and aggregates vary in composition like those of other CM chondrites. They are Ca-,Al-,Si-poor and Mg-,Fe-rich relative to composition of surviving chondrule glass of some CM chondrites but they are Ca-,Al-rich and Mg-,Fe-poor as compared to olivine. Sometimes secondary phases are enriched in Na and P.

The **opaque mineral** assemblage of Dhofar 225 is also unusual for CM chondrites. FeNi metal phases were found in all constituents of Dhofar 225, except for CAIs. Metal inclusions in Fo-rich olivines are poorer in Ni (5.5 wt.%) and Co (0.24 wt.%) than FeNi -metal of sulfide-metal aggregates and separate metal grains in the matrix. This metal is taenite and tetrataenite with high Co (up to 66.2 wt.% Ni; 2.1 wt.% Co). No Cr and P were detected in FeNi - metal of Dhofar 225. Similar metal compositions were described in the Belgica 7904 and Y 86720, metamorphosed carbonaceous chondrites [3].

Typical **accessory sulfides and phosphides** are pentlandite, Ni-pyrrhotite, troilite and schreibersite. P-rich sulfides, which are usual accessory phases of CM chondrites [4], were not found in Dhofar 225. Phyllosilicate inclusions in the matrix contain schreibersite, eskolaite, and rare Cr-barringerite $Fe_{1.3}Cr_{0.7}P$ with a low Ni content. The **Ca, Fe oxysulfide** is a rare phase, found as irregular, rounded 10-20 μm inclusions in the matrix. The inclusions consist mainly of small oxysulfide grains, which are yellowish gray and show bireflectance in reflected light. Small grains of pyrrhotite are often present at the edges of the inclusions. The inclusions also contain thin veins of a fayalite-like phase and small blebs of Fe hydrooxide. The Ca, Fe oxysulfide has a fixed composition with contents (wt%) of Fe 42.1; Ca 22.2; S 19.1, total 83.6. Fe/S and Ca/S atomic ratios are 1.26 ±0.05 (1δ) and 0.93± 0.08 (1δ), i.e., there is an Fe excess relative to Ca and S. EDS spectra and the low total suggest that oxygen may be presente. The best-fit chemical formula is $Ca_{4.66}Fe^{2+}_{0.34}Fe^{3+}_{6}S_5O_9$. Another possible formula, which includes (OH) groups, is $Ca_4Fe^{2+}_5S_4(OH)_4O_3$.

The bulk chemistry of Dhofar 225 is atypical for the CM clan of meteorites although Mg/Si and Al/Si ratios are similar to those of CMs. The H_2O-content of Dhofar 225 (1.76 wt.%) is lower than that of CM chondrites (2-16 wt.%) [5]. The bulk Fe/Si ratio of Dhofar 225 is lower in comparison with CM and carbonaceous metamorphosed chondrites (Belgica 7904, Y 82162, and Y 86720 [6]).

The matrix is strongly depleted in Fe and S relative to other CM matrices [7] and similar in composition to the matrix of the Y 86720 metamorphosed carbonaceous chondrite. However the Dhofar 225 matrix is close in Mg/Si and S-Ni-Mg-Si relationships to CM chondrite matrices [7,8,9].

Discussion. Dhofar 225 shows moderate abundance of secondary phases. The mineralogic alteration index (M.A.I.) [10] of Dhofar 225 phyllosilicates is 0.76, and similar to that of Mighei (0.77) and Boriskino (0.73) phyllosilicates, and consistent with mineralogical observations.

Fe contents of CM matrices decrease relative to Si with increasing degree of secondary alteration [7]. In the Fe-Si-Mg ternary diagram, the average composition of the Dhofar 225 matrix plots close to CI chondrite matrices and the Y 86720 and Y 82162 matrices, which are thought to be extremely altered. It conflicts with the moderate abundance of secondary phases in Dhofar 225. Interestingly, the Fe/Si bulk and matrix ratios of Dhofar 225 are the same in contrast to any other known CM chondrites.

Dhofar 225 contains pentlandite and pyrrhotite, but also troilite, kamacite, taenite and tetrataenite. Fine-grained sulfides probably could have been formed from the matrix during thermal metamorphism. Ni as a siderophile element could migrate from sulfides to FeNi -metal under increasing temperature [7].

Thermal metamorphism is consistent with the bulk low H_2O content of this meteorite and the totals of matrix EPM analyses that are relatively higher than the totals of CM matrices. Belgica 7904, Y 86720 and Y 82162 also have relatively low - H_2O contents and the totals for their matrix analyses, and the meteorites are thought to be affected by heating [6,8]. However, the sharp zoning of olivine grains in some of the chondrule-like objects in Dhofar 225 is inconsistent with significant thermal metamorphism of this meteorite. The heating should have been sufficient only for dehydration. Such sharply zoned olivine grains were not described in any CM and metamorphosed carbonaceous chondrites. With the estimated temperature of metamorphism in Belgica 7904 of > 700°C [11], it is unusual to have olivine grains preserve such chemical zoning. This metamorphism that occurred must have been of relatively short duration to have maintained the olivine zoning profiles.

The presence of Ca,Fe oxysulfide, Cr-barringerite, as well as eskolaite, schreibersite, troilite, taenite and tetrataenite in the Dhofar 225 matrix indicates a mixing of material formed under different redox conditions.

In summary, Dhofar 225 is an anomalous carbonaceous chondrite,- that demonstrates some characteristics of CM chondrites: texture, basic mineralogy, bulk chemistry and matrix composition. However, it also has some similarities to metamorphosed carbonaceous chondrites: e.g., similar oxygen isotopic composition, low - H_2O- content, high totals of matrix analyses, and the presence of tiny grains of tetrataenite in the matrix. In distinct contrast to these observations, the sharp zoning of olivine in the chondrule-like objects of Dhofar 225 appears to negate significant metamorphism and suggests only moderate or low heating event.

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