

GEOCHEMISTRY

Polyfacies Mode of Igneous Rocks and Meteorites

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The polyfacies mode of rocks and meteorites is related to their formation in several stages, which strongly differ in *PT* conditions. The polyfacies mode appears in igneous rocks during crystallization of magma owing to decrease in lithostatic pressure (depth) at the following stages: primary magma chamber–intermediate magma chambers–final consolidation of magma in intrusions or volcanic effusions (low-pressure minerals and volcanic glass). In contrast, minerals transported from deep-seated chambers are represented by high-pressure abyssal modifications. In crustal rocks, they can only occur as accessory or rock-forming minerals. For instance, the Ust-Khannin gabbro–dolerite intrusion ascribed to the trap association of the Siberian Craton [5, 6] contains accessory orange pyrope–almandine (data in parentheses) and pale violet pyrope (wt %): SiO₂ 40.22 (41.22), TiO₂ 0.37 (1.03), Al₂O₃ 13.44 (21.28), Cr₂O₃ 11.02 (0.28), FeO 7.29 (10.14), MnO 0.44 (0.31), MgO 18.29 (20.73), CaO 6.38 (4.49), Na₂O 0.10 (0.06), and total 97.70 (99.54).

They reflect the formation of primary ultramafic melt due to the melting of mantle protolith with the crystallization of pale violet Cr-pyrope. Subsequent mafic–ultramafic layering of the primary melt was accompanied by unmixing of basaltic magma, which inherited pale violet garnet of primary melt, and the simultaneous crystallization of its own pyrope–almandine garnet. This magma formed gabbro–dolerites with specific accessory mineralization represented by garnets of diverse composition and color (Fig. 1). The garnet crystallized in mantle under ultrahigh lithostatic pressure, and its presence in gabbrodolerites (subvolcanic rocks) defines their wide polyfacies mode.

Orange and pale violet garnets of gabbrodolerites are similar to garnets of eclogite and pyrope peridotites, respectively, whose associations are widespread in nodules of kimberlite pipes and in foldbelts with magmatism genetically related to mantle-related magma sources. Crystallization of magmas in the course of

their emplacement into the Earth's crust is recorded in the development of reverse zoning in minerals of variable composition (e.g., enrichment of rims in refractory components). This is caused by decrease of lithostatic pressure with corresponding decrease of magma crystallization temperature and shift of the crystallization temperature (solidus) of minerals of variable composition toward refractory components [3].

In garnet solid solutions, the refractory component is represented by pyrope, whose content increases toward the rim relative to almandine and grossular, thus forming a reverse zoning with ascent of eclogitic magmas. The reverse zoning is typical of eclogites of both foldbelts and kimberlite pipes, suggesting their similar genetic relation with mantle-related magma chambers. The widest range of reverse garnet zoning is typical of diamondiferous eclogites [3] emplaced in the Earth's crust from abyssal chambers (150–300 km). This fact is recorded in diamond and mineral inclusions therein, which make it possible to classify diamond grains into genetic (peridotite, pyroxenite, and eclogite) types corresponding to the compositions of parental magmas. These types of diamond reflect the mafic–ultramafic unmixing of magma chambers prior to crystallization.

Diamond is characterized by the abundance of sulfide inclusions (pyrrhotite inclusions in the eclogite diamond and pyrrhotite–pentlandite solid solutions in peridotite diamond). This feature reflects the genetic relation of diamonds to ferruginous derivatives of the aforesaid parental magmas, which were sulfurized under the action of H₂- and CS₂-rich transmagmaic flu-

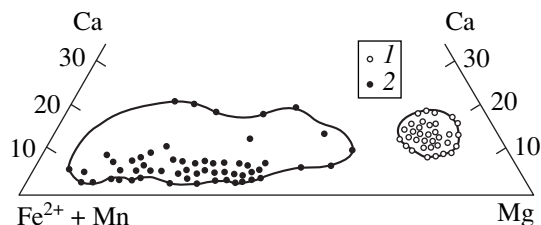


Fig. 1. Compositional diagram of garnets contained as accessory minerals in gabbrodolerites and basalts in the Siberian Craton and Kamchatka (after [5]). (1) Knorringite-rich pyropes, (2) low-Cr pyrope-almandines.

ids: $\text{MgFeSiO}_4 + (\text{H}_2 + 0.5\text{CS}_2) = \text{MgSiO}_3 + 0.5\text{C}$ (diamond) + $\text{FeS} + \text{H}_2\text{O}$.

The fluid regime of diamond formation is also characterized by the presence of high-density gas inclusions (H_2 , H_2O , CO , CO_2 , CH_4 , N_2 , noble gases, etc.). However, terrestrial diamond in this respect is notably inferior to meteorite-hosted and, especially, chondrite-hosted diamond, as illustrated in Fig. 2 and the table for noble gases. The abundance of fluid inclusions in meteorite diamond is so high that the volume density of its tiny grains is nearly 2.2 g/cm^3 (diamond density 3.5 g/cm^3). This indicates the crystallization of diamond at very high fluid pressures atypical of planets of the Earth group and typical of only giant planets of the Jupiter group. Analogues of the latter group were represented by near-solar protoplanets, in the core of which chondrite magmatism originated and evolved under super-high pressures of their fluid envelopes [2, 4].

When the giant protoplanets lost fluid envelopes under the action of the Sun, their chondritic liquid cores were transformed into independent iron–stone planets of two types. Planets of the Earth group were differentiated into fluid–melt iron cores and solid silicate envelopes that prevented the process of breakup. The distal (relative to the Sun) chondrite planets were still in an undifferentiated state. Their explosion produced a fragmented asteroid belt, which served as the source of meteorites (mainly chondrites). Chondrites distinctly demonstrate two-stage evolution. The protoplanetary stage proceeded under ultrahigh fluid pressure indicated by diamond formation, whereas the planetary stage was characterized by low pressure. Their combination in chondrites defines the polyfacies mode characterized by a very wide pressure range.

The protoplanetary stage also includes unmixing of chondrite melts into silicate chondrule drops and taenite–kamacite matrix, in which diamond nuclei formed in association with moissanite (SiC), troilite, and, occasionally, chromite. When protoplanetary fluid envelopes lost hydrogen under the influence of the Sun, the chondrule–matrix equilibria in the melts shifted in a stepwise manner toward an increase in the iron mole fraction in silicates with the formation of magmatic series, including a wide range of chemical groups of chondrites, for example, ordinary chondrites: $0.75\text{Mg}_{1.6}\text{Fe}_{0.4}\text{SiO}_4 + 0.25\text{Mg}_{0.8}\text{Fe}_{0.2}\text{SiO}_3 + 0.25\text{Fe} + 0.25\text{H}_2\text{O} = \text{Mg}_{1.4}\text{Fe}_{0.6}\text{SiO}_4 + 0.25\text{H}_2$.

Content of noble gases (cm^3/g) in (1) diamond and (2) moissanite from carbonaceous chondrites, (3) diamond from ureilite, and (4) terrestrial diamond

Ordinal no.	Mineral	^4He	^{20}Ne	^{36}Ar	^{84}Kr	^{132}Xe	Reference
1	Diamond	$3.64 \cdot 10^{-2}$	$9.14 \cdot 10^{-5}$	$5.20 \cdot 10^{-5}$	$3.48 \cdot 10^{-7}$	$2.88 \cdot 10^{-7}$	[10]
2	Moissanite	$8.19 \cdot 10^{-2}$	$6.39 \cdot 10^{-8}$	$5.31 \cdot 10^{-6}$	$1.56 \cdot 10^{-7}$	$1.52 \cdot 10^{-7}$	[11]
3	Diamond	$3.15 \cdot 10^{-5}$	$9.35 \cdot 10^{-7}$	$1.49 \cdot 10^{-4}$	$5.14 \cdot 10^{-7}$	$2.8 \cdot 10^{-7}$	[9]
4	Diamond	$9.68 \cdot 10^{-6}$	$7.55 \cdot 10^{-10}$	$5.62 \cdot 10^{-10}$	$4.13 \cdot 10^{-11}$	$2.14 \cdot 10^{-12}$	[12, 15]

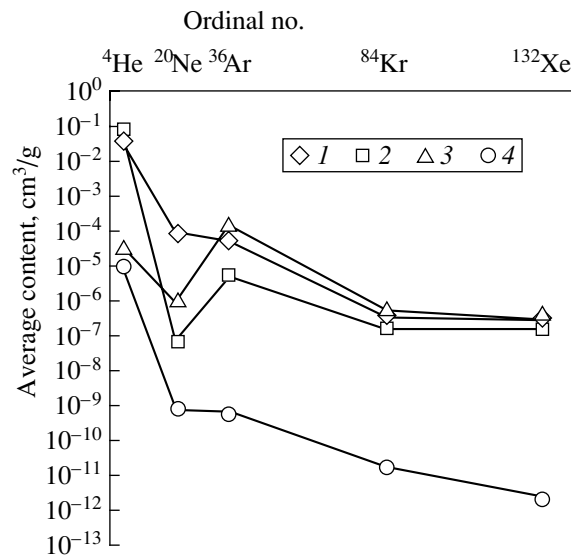


Fig. 2. Comparison of (1) diamond and (2) moissanite from carbonaceous chondrites with diamond from (3) ureilites and (4) kimberlite pipes based on noble gas contents (cm^3/g) (after [9–12, 15]).

The reaction shows that H_2O – H_2 proportions in the fluid envelopes of chondrite protoplanets is the main factor defining the iron mole fraction in silicates. An increase in the iron mole fraction of chondrule in chondrites correlates with an anomalous concentration of heavy oxygen isotope. This is from the average compositions of HH-, H-, L-, and LL-chondrites in Fig. 3 ($\tan\alpha = 1.0$). Such an anomalous isotopic composition of the magmatic series of ordinary chondrites is caused by its evolution under extremely high fluid pressure provided by parental protoplanets. However, chondrules crystallized later at the low-pressure planetary stage. This process was accompanied by the normal process of oxygen isotope fractionation between minerals ($\tan\alpha = 0.5$), which is characterized in the diagram by tie-lines that connect mineral compositions. At this stage, the oxygen isotope fractionation was already similar to that of terrestrial and lunar rocks, shown in the diagram for comparison.

Carbonaceous chondrites, e.g., the Murchison chondrite, have the highest diamond content (up to 400 g/t) [13]. Like all chondrites, this meteorite contains diamond in association with moissanite (SiC), although its

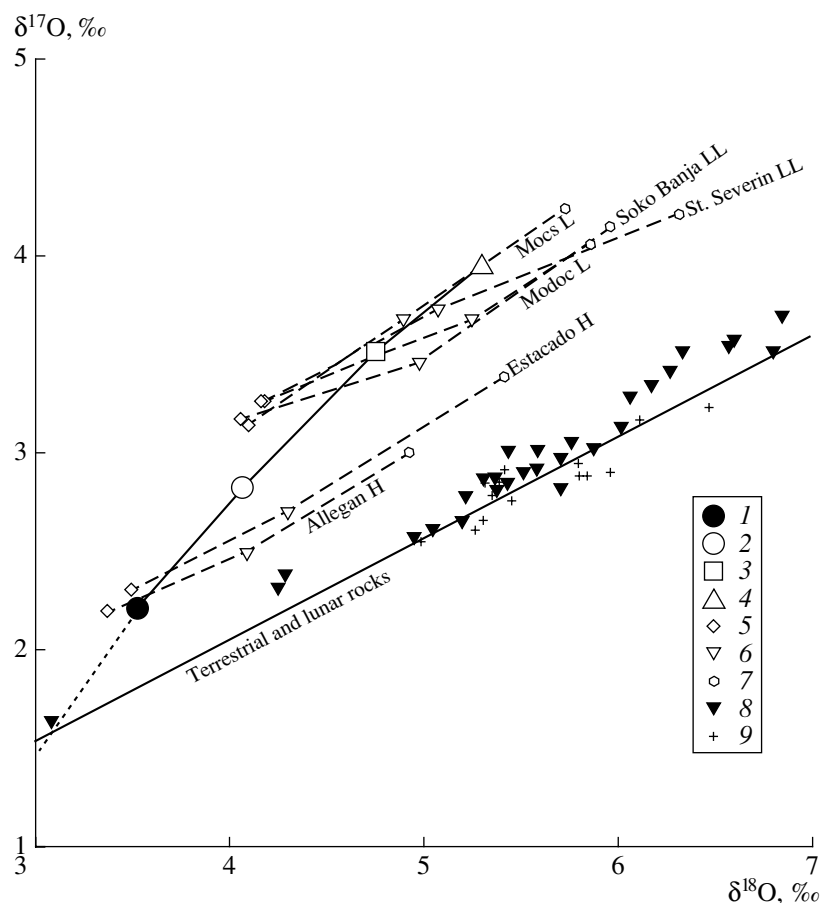


Fig. 3. Comparison of oxygen isotopic compositions. Named ordinary chondrites (average compositions): (1) HH (Nechaevo) chondrite, (2) H, (3) L, (4) LL (4); chondrite minerals: (5) olivine, (6) pyroxene, (7) plagioclase; rocks: (8) terrestrial, (9) lunar [7, 8, 14].

content is as low as 7 g/t because of the ultramafic composition of the Murchison meteorite. In more silicic enstatite chondrites, moissanite may be more abundant

and this mineral may predominate over diamond. Hence, the moissanite–diamond association is consistent with petrochemical composition of chondrites.

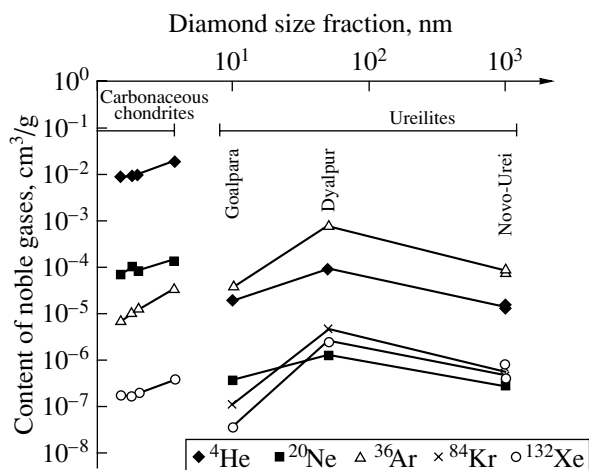


Fig. 4. Contents of noble gases in diamond versus its grain size in the Efremovka carbonaceous chondrite (CV3) and Goalpara, Dyalpur, and Novo-Urei ureilites [1].

The family of carbonaceous chondrites also includes ureilites. They represent primitive pigeonite–olivine achondrites with aggressively superimposed diamondiferous kamacite–graphite mineralization along olivine–pyroxene grain boundaries and as small veins. The mineralization is related to recrystallization of minerals accompanied by a decrease in the primary iron mole fraction (16–20) to almost zero values and exsolution of native iron. Unlike the Ni-bearing kamacite (5–6% Ni) of diamondiferous intrusions, the native iron is almost completely lacking in this element. Diamond of ureilites is similar in many respects to that of carbonaceous chondrites, except for the larger grain size and some specifics of the noble gas composition (Fig. 4). These features indicate that ureilite had already formed at the protoplanetary stage of immiscible splitting of the primary carbonaceous chondrite planet into a kamacite liquid diamondiferous core, ureilite mantle, and plagioclase crust. The subsequent emplacement of diamondiferous kamacite melt in the ureilite mantle accompanied by the metastable growth of diamond grains provided

for diamond concentration in ureilites, which represent meteorites of a specific polyfacies mode. Exhumation of diamondiferous kamacite melts was accompanied by loss of light noble gases. Their content in the partially metastable diamond of ureilites is lower relative to the carbonaceous chondrites.

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