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**GEOCHEMISTRY**

# Water Inclusions in Lechatelierite from Impact Fluidizites of the Popigai Astrobleme

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Endogenic fluidizites and tuffizites have been known for a long time and are rather abundant in the Earth's crust [1, 2]. They are formed by emplacement of hot fluid–melt mixtures under a high excess pressure. Such rocks have not only academic significance, but also important economic implications, because deposits of ferrous, nonferrous, rare, and noble metals are often associated with them. The study of impact structures—the Popigai astrobleme, in particular—has shown that the products related to the emplacement of fluidized, high-mobile material can appear in the course of both endogenic and impact processes. The Popigai impact fluidizites, which have been recognized for the first time as a special class of rocks in terrestrial astroblemes, were preliminarily described in [3, 4].

The Popigai astrobleme, 100 km in diameter, is a unique meteoritic terrestrial crater. Its impact origin has been substantiated by numerous attributes of shock metamorphism, including finds of high-pressure minerals, such as impact diamond [6], coesite [7], and stishovite [8].

The impact fluidizites were found in megabreccia at the western wall of the Popigai. The megabreccia is widespread in this astrobleme and exposed as a belt (4–15 km wide) around its periphery (Fig. 1). This is a chaotic mixture of large blocks of target rocks, 1–100 m in size, incorporated into psammitic–psephitic products of more intense crushing. The clastic matrix of megabreccia often contains variable amounts of impact glass as small particles and fluidal streams of variable dimensions. The composition and structure of megabreccia indicates that the clastic material was supplied from different areas of explosive transformation of target rocks, including zones of impact melting, shock metamorphism, and crushing.

The impact fluidizites occur as dikes of fine-clastic tufflike material in gneiss blocks from the megabreccia. These branching dikes are composed of glass particles

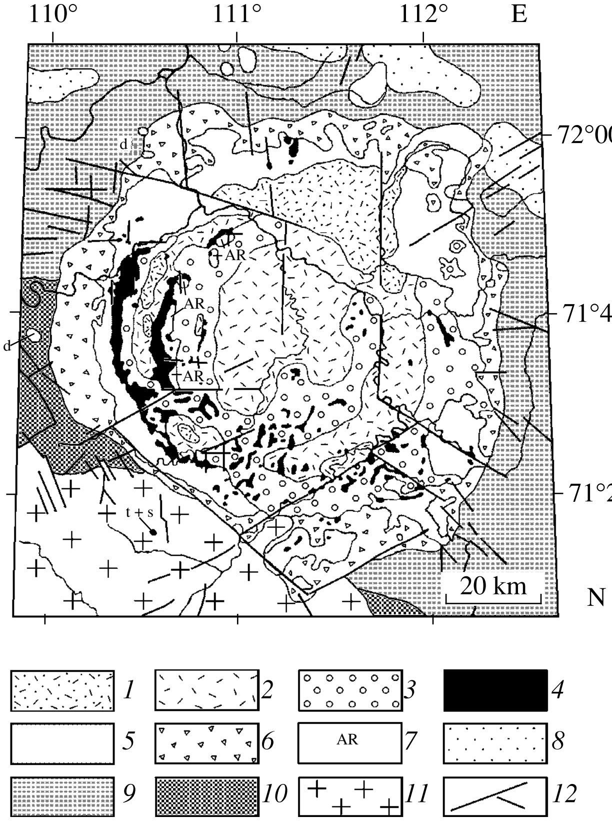

**Fig. 1.** Geological scheme of the Popigai astrobleme, modified after [5]. (*1–3*) Deposits of explosion cloud: (*1*) suevite megabreccia, (*2*) Daldyn-type suevite, (*3*) Parchanai-type suevite; (*4–6*) deposits of centrifugal bottom flow: (*4*) tagamite, (*5*) megabreccia, (*6*) klippen breccia; (*7*) paraautochthonous products from the plastic flow zone (shocked gneiss of the inner ring swell); (*8–11*) target rocks: (*8*) Mesozoic, (*9*) Paleozoic, (*10*) Proterozoic, (*11*) Archean; (*12*) faults. The Pastakh and Ed'en-Yureg impact diatremes (western and northwestern walls of astrobleme, respectively) are denoted by index d, while tagamite and suevite cover in the southeastern framework of the astrobleme, by index t+s.

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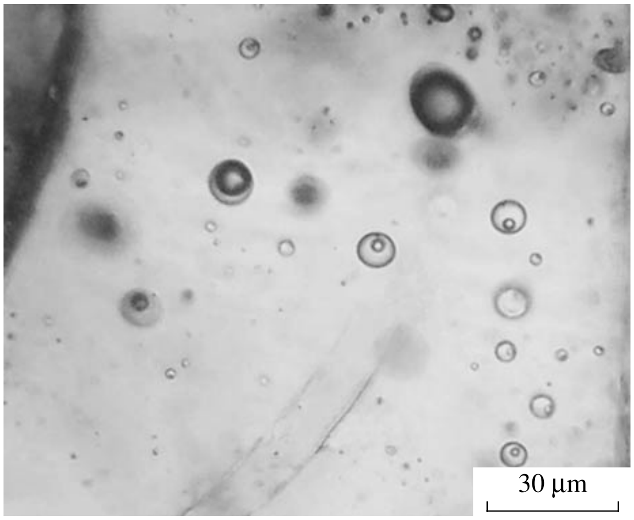

**Fig. 2.** Syngenetic water inclusions of variable density in lechatelierite from the Popigai impact fluidizites. Sample 2379-2a-1, schliere 4, photomicrograph 8419, plane light.

(10–90 vol %), fragments of host gneisses, and cryptocrystalline groundmass. The main mass of glass forms porous schlieren that are welded with other components of the rock. However, some of the glass occurs as fragments. The glasses are divided into structurally homogeneous and predominant apogneiss varieties (type I) and the structurally heterogeneous variety (type II) composed of alternating thin bands of femic (enriched in Fe and Mg), felsic (enriched in Si, K, and Na), and apogneiss glasses. Purely felsic glass (type III) is also known. Part of this variety is represented by coesite-bearing lechatelierite schlieren and fragments of diaplectic quartz glass. The low total content of oxides and high porosity indicate a high content of volatile components (2–4 to 12 wt % or more) in the glass at the moment of its formation. This inference has been supported by direct determination of 1.11–8.97 wt % $H_2O$ in glass (based on ion microprobe). The glass contains shadows of femic minerals of the parent rock, as well as globules of magnetite, native iron, zircon, and rutile, which are products of melting or decomposition of some initial minerals at a high temperature (>1590, >1530, ~1800, and >1850°C, respectively). Coesite and diaplectic quartz glass in association with high-temperature minerals clearly indicates the impact origin of fluidizites.

As follows from the bulk chemical composition of glass and its heterogeneity, the hyaline component of the rock is a product of fluid–melt mixture, which was formed after target gneisses in the marginal zone of impact melting. It is known that such melting of gneisses occurs at a shock pressure of ~50–60 GPa. Based on the theory of impact crater formation, the radius of zone of impact gneiss melting in Popigai is estimated at 14–15 km. The gneiss blocks with impact fluidizite dikes and the gneiss fragments therein do not reveal petrographic indications of shock metamorphism. According to the known scales of shock metamorphism of quartz and feldspars, the host gneisses were located in a zone of weak shock metamorphism under a pressure of <8–10 GPa. In Popigai, the radius of this zone is estimated at >25–30 km from the explosion center.

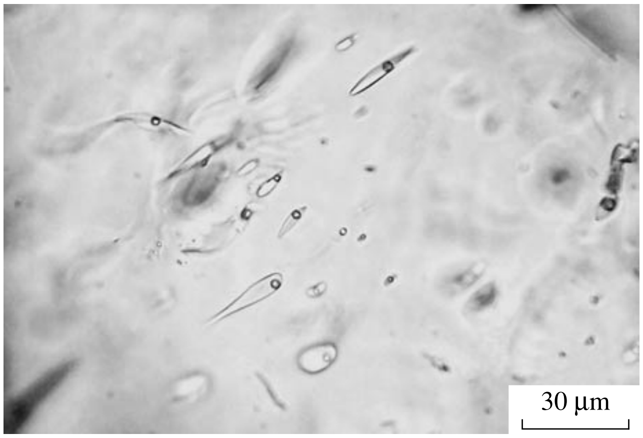

**Fig. 3.** A group of syngenetic water inclusions with predominant liquid phase in lechatelierite. Sample 2379-2a-1, schliere 1, photomicrograph 8401, plane light.

The lechatelierite schlieren contain numerous syngenetic fluid inclusions of variable density: gas inclusions, gas–liquid inclusions with variable proportions of gas and liquid phases, and even completely liquid inclusions at 20°C (Figs. 2, 3). Since the melted silica has a high temperature of vitrification, the inclusions in lechatelierite attract special interest, because they bear information on the earliest stages of dike formation.

According to the cryometric measurements (table, Fig. 4), the liquid phase of inclusions is represented by water with a low salinity (0.5–8, generally <2 wt % NaCl equiv). The bulk density of the studied water inclusions varies from ~0.1 g/cm$^3$ (table, inclusions 5a–10a) to ~1 g/cm$^3$ for inclusions that become completely liquid at 20°C.

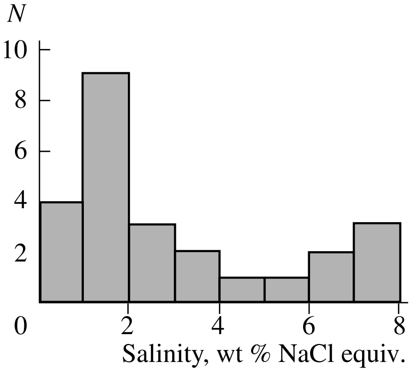

**Fig. 4.** Bar chart of water salinity in inclusions from fused silica schlieren (based on 25 analyses). (*N*) Number of analyses.

Results of the cryometric study of fluid inclusions in lechatelierite from impact fluidizites in the Popigai astrobleme (sample 2179-2a-1, schlieren 1 + 2, fragments a–c)

| Inclusion nos. in zones a–c | Inclusion type | Proportion of liquid and gas at 20°C | Eutectic temperature, °C | Temperature of ice melting, °C | Salinity, wt % NaCl equiv |
|---|---|---|---|---|---|
| 1a | $L_{H_2O}$ + G | 80 : 20 | –23.2 | –0.3 | ~0.9 |
| 2a | $L_{H_2O}$ + G | 60 : 40 | –25.4 | –0.7 | ~1.6 |
| 3a | $L_{H_2O}$ + G | 80 : 20 | –23.8 | –0.9 | ~2 |
| 4a | $L_{H_2O}$ + G | 80 : 20 | –26.1 | –1.6 | ~3.5 |
| 5a | G + $L_{H_2O}$ | 10 : 90 | n.a. | n.a. | n.a. |
| 6a | G + $L_{H_2O}$ | 10 : 90 | " | " | " |
| 7a | G + $L_{H_2O}$ | 10 : 90 | " | –0.5 | ~1.5 |
| 8a | G + $L_{H_2O}$ | 10 : 90 | " | n.a. | n.a. |
| 9a | G + $L_{H_2O}$ | 10 : 90 | " | –0.9 | ~2 |
| 10a | G + $L_{H_2O}$ | 10 : 90 | " | n.a. | n.a. |
| 1b | $L_{H_2O}$ + G | L > G | –29.5 | –0.9 | ~2 |
| 2b | $L_{H_2O}$ + G | L > G | –29.3 | –1.2 | ~3 |
| 3b | $L_{H_2O}$ + G | G > L | –25.5 | –0.9 | ~2 |
| 4b | $L_{H_2O}$ + G | G > L | –26.3 | –1.3 | ~3.1 |
| 5b | $L_{H_2O}$ + G | L > G | –24.8 | –2.7 | ~5.5 |
| 6b | $L_{H_2O}$ | 100 : 0 | –32 | –3.5 | ~7 |
| 7b | $L_{H_2O}$ | 100 : 0 | –31.4 | –3.7 | ~7.2 |
| 8b | $L_{H_2O}$ + G | L ~ G | –29.1 | –2.1 | ~5 |
| 9b | $L_{H_2O}$ + G | L > G | –27.5 | –0.3 | ~0.9 |
| 1c | $L_{H_2O}$ | 100 : 0 | –30 | –0.1 | ~0.5 |
| 2c | $L_{H_2O}$ | 100 : 0 | –30.5 | –1.4 | ~3.2 |
| 3c | $L_{H_2O}$ + G | 90 : 10 | –25.6 | –0.5 | ~1.5 |
| 4c | $L_{H_2O}$ + G | 90 : 10 | –25.9 | –0.6 | ~1.7 |
| 5c | $L_{H_2O}$ + G | 90 : 10 | –25.2 | –1.1 | ~2.8 |
| 6c | $L_{H_2O}$ + G | 90 : 10 | –23 | –0.9 | ~2 |
| 7c | $L_{H_2O}$ + G | 90 : 10 | –20.5 | –3.5 | ~7 |
| 8c | $L_{H_2O}$ | 100 : 0 | –24.8 | –4.2 | ~8 |
| 9c | $L_{H_2O}$ + G | 70 : 30 | –12.1 | –3.7 | ~7.2 |
| 10c | $L_{H_2O}$ + G | 80 : 20 | –16.3 | –1.8 | ~4 |

Note: Freezing temperature fell to –180°C in zones a and b and to –120°C in zone c; water is frozen out as films and elongated crystals in gas-rich inclusions 7a and 9a; in addition to $H_2O$, isolated $CO_2$ crystals with melting temperature of –57°C are frozen out in gas-rich inclusions 3b and 4b; (n.a.) not analyzed.

At a first glance, the presence of dense or completely liquid inclusions in the lechatelierite is enigmatic, because the high pressure required for their conservation is impossible under conditions of the Earth's surface. Indeed, the minimum temperature of metastable quartz melting is ~1450°C [9]. However, the magnetite, native iron, zircon, and rutile globules observed in the glass show that the temperature of the silica schlieren could have reached 1800–1900°C; an estimate of ~1700°C is highly realistic. According to the phase diagram of water [10], the pressure at conservation of water inclusions with density of 0.5–1.0 g/cm$^3$ at 1700°C should be ~0.8–3.3 GPa at a schlieren temperature of ~1700°C.

The Popigai impactites, including megabreccia, are strictly surface products, and the total thickness of their cover in the marginal part of the astrobleme was not greater than 0.3–0.5 km. Therefore, the lithostatic version of high pressure estimated from inclusions in lechatelierite is completely ruled out at the stage of postimpact evolution of astrobleme. This implies that the fluid–melt mixtures of fluidizite dikes intruded into gneiss with a certain residual shock pressure that provided high mobility of these mixtures. Since the host gneisses and source of fluid–melt material were initially located in different zones of shock metamorphism, the residual shock pressure of these mixtures was retained even after their being significantly (12–15 km) displaced from of the generation zone to the point of dynamic contact with gneisses. This is impossible in dry systems with fast relaxation of shock pressure by wave mechanism, when the relaxation front moves at the speed of sound in the compressed medium.

In this connection, we suggest that it was precisely the volatile components that were abundant in enormous masses of the Popigai impact melt that were responsible for the slow relaxation of melts at the stage of centrifugal spreading during excavation of the crater. The decelerated relaxation of fluidized media is known from shock experiments with wet systems [11], which show that, beginning from a certain moment, the relaxation of the compressed hydrous system is controlled by the behavior of water, the volumetric expansion of which is several orders of magnitude higher than that in dry silicate melts. In [12], we pointed out that, at such a significant expansion, the compressed water inclusions work against the force of viscous friction and the entire fluidized system relaxes at any real viscosity of melt by means of a much slower "piston" mechanism rather than by wave propagation. Therefore, water contained in the "wet" impact melt behaves as a buffer-decelerator of relaxation.

This effect may explain the high residual pressure of fluid–melt mixtures in the astrobleme at the moment of their emplacement into the target gneisses after having been displaced over a distance of no less than 12–15 km (from the generation region in the marginal zone of impact melting to the contact point in the zone of weak shock metamorphism). The buffer role of water in deceleration of relaxation of "wet" shock-compressed media will be valid for a wide range of granitoids and other crystalline crustal rocks that always contain a certain amount of pore-fissure (interstitial) and constitution water. These rocks are affected by impact melting at a shock pressure of >50–60 GPa.

Previous works have already highlighted the important and complex contribution of water in the mineral genesis (as a catalyst of coesite growth [12, 13]), the petrogenesis (zhamanshinite facies of impact glasses in some astroblemes), the separation of components (impact anatexis of the Popigai shock-compressed gneisses with the release of melts enriched in Si, K, and volatiles [5]), and the specific excavation of shocked material in large astroblemes (formation of suevite–tagamite megamixtures in the Popigai astrobleme [15]). The results of our investigations show that relatively long-lived and extremely mobile systems with residual shock pressure and high penetrability may arise in the wet shocked material. This specific feature of fluid regime in impactites should be taken into account in mineralogical, petrological, and geological investigations of terrestrial astroblemes and in reconstructions of impact crater formation on Mars and other planets where the rocks are enriched in water and other volatile components.

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