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Geodynamics, Petrology, and Mineralogy: Global Problems, Experiments, and Key Cases

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This Special Issue of Russian Geology and Geophysics is devoted to the memory of Vladimir Stepanovich Sobolev, Full Member of the Russian Academy of Sciences, whose ideas have been a leading light for his numerous disciples and became implemented in many present-day research projects. The contributions to the Special Issue are split into two parts that focus on global problems in geodynamics and petrology and on experimental studies. In addition to twelve new works, this review includes the paper of Guillot et al. (2019) which was published previously in Russian Geology and Geophysics and is relevant to the topics.

The overview by N. Dobretsov "Plate Tectonics vs. Plume Tectonics Interplay: Possible Models and Typical Cases" opens the Special Issue and is the first among six papers of part 1. It concerns the problems of plate tectonic and plume tectonic mechanisms in global geodynamics, which were discussed at the international conference on large igneous provinces (LIP-19, September 2019, Tomsk) co-chaired by R. Ernst, V. Yarmoluk, and N. Dobretsov.

New seismic tomography images of the D_2 layer (Dobretsov, 2020 and references therein) reveal plumes that are rooted at the core-mantle boundary and have surface signatures. They are twenty primary and clearly detectable plumes (type I) localized in two major zones of low shear velocities with negative $\delta\, v_s/v_s$ ratios (French and Romanovich, 2015). Plumes in the African province (Zonenshain and Kuzmin, 1983), otherwise called Tuzo (Torsvik and Cocks, 2017), extend from the Iceland plume in the north to the Kerguelen plume in the Indian Ocean, through the Afar, Tanzania, Canary, and Cabo Verde plumes within or near Africa. The Pacific or Jason (Torsvik and Cocks, 2017) province in the central and southwestern Pacific Ocean accommodates the Hawaii plume in the north and Pitcairn, Samoa, Tahiti, Macdonald, and Marquess plumes south of it. Circular features in the plume fields record the convection pattern in D_2.

Other plumes (type II), located in the vicinities of mid-ocean ridges, are often attributed to the lower mantle, but they actually have lost their deep roots, partly (Galapagos, Tristan, St. Helena) or completely (Bouvet, Crozet). Possible reasons are mixing with upwelling asthenospheric material or transformation at the lower/upper mantle interface or at the base of the asthenosphere. Further studies are required to provide more rigorous constraints on the place and mechanisms of this transformation, including by modification (mixing) of carbonatite melts rising from the lower mantle.

The origin of mantle plumes at the core-mantle boundary shows up in high $^3He/^4He$ ratios, especially in the Hawaii, Iceland, and Reunion plumes (Fig. 3 in (Dobretsov, 2020)); high contents of PGE and O_s isotopes (Hansky et al., 2004; Izokh et al., 2016); and in negative correlation with the frequency of geomagnetic polarity reversals (Larson and Olsen, 1991; Dobretsov et al., 1997, 2001). The correlation of plume magmatism with polarity reversals has important implications for the nature of the geomagnetic field and the role of plumes in plate motion. The 20–40 myr long events of most voluminous plume magmatism (around 1,000,000 km^3 or more per 1 myr) are accompanied by faster

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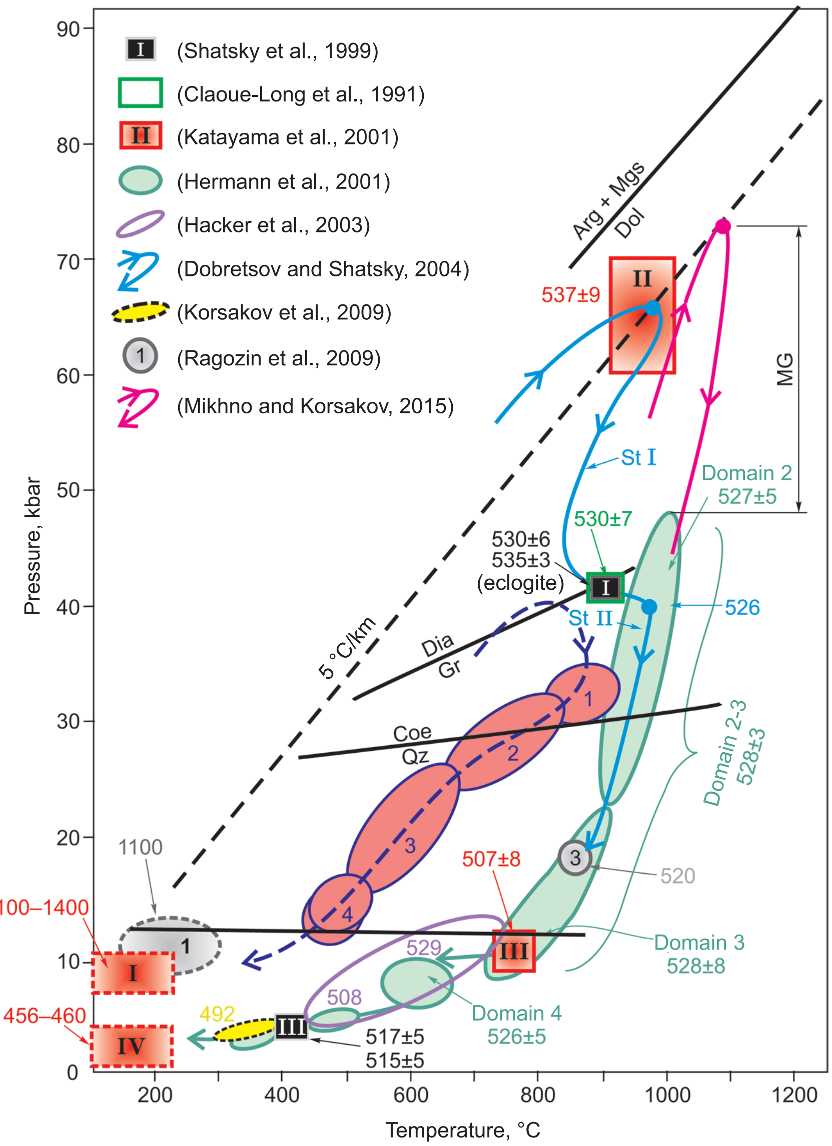

Fig. 1. Comparison of *P–T* exhumation paths for igneous rocks of the Kokchetav paleosubduction zone based on the data from Dobretsov and Shatsky (2004); Schertl and Sobolev (2013); Dobretsov et al. (2015); Mikhno and Korsakov (2015) and with the stages of metamorphism in the Maksyuta complex – red ovals – 1–4. Source: Sobolev et al., 2015, edited.

plate velocities (increasing from 2–4 cm/yr to 20–25 cm/yr) and stable geomagnetic polarity (at 84–124 Ma and 263–233 Ma) indicating the absence of overheating and stable convection in the liquid core. Two other regimes of geomagnetic activity (Bazhenov et al., 2016; Levashova et al., 2020) correspond to predominant polarity with 1 to 4 reversals per 1 myr (up to 6 reversals per 1 myr in the past 5–15 Ma) and high activity with 10–16 reversals per 1 myr (late and early Cambrian).

The model of lower mantle plumes, which was published previously (Dobretsov and Kirdyashkin, 1994; Dobretsov et al., 2001; Dobretsov, 2011) and is sketched in this paper, reveals three stages in the plume-related magmatic activity and predicts the formation of a mushroom-shaped plume head (Dobretsov et al., 2001). The model allows estimating the amount of heat stored in plumes and their head sizes ($12–20 \times 10^6$ km^2 at $1.2–1.5 \times 10^9$ kW for the Siberian trap province), and the estimates are consistent with available data on the Hawaii, Siberia, and some other major plumes. The intensity of plume activity correlates with velocities of plates in the northwestern Pacific and the adjacent Arctic areas for the past 150 Ma. However, the correlations reported in the paper are tentative and not yet global-scale; no models have been obtained for specific plume histories, asthenosphere heating, and plate acceleration due to dissolution of some hot plumes in the asthenosphere.

In conclusion, the paper considers large continental provinces of plume magmatism, including the Siberian Trap Province, and related metallogeny (Sobolev, 1936; Borisenko et al., 2006; Dobretsov et al., 2010). One of the teachers of V.S. Sobolev at the Mining Institute, A.N. Zavaritskii, writes in a brief preface to the book (Sobolev, 1936), published when Sobolev was 28 years old: "The book authored by V.S. Sobolev is a comprehensive monograph on a group of rocks which is highly important for the geology of a vast territory of our country and interesting in terms of solving some theoretical issues of petrology in general. The monograph is aimed at studying Siberian traps but also presents a discussion of traps worldwide, in which the author does not restrict himself to compiling other researchers' statements and opinions and gives a valuable critical overview of literature on the issue. The book focuses extensively on trap magma crystallization and differentiation." The previous model of Siberian trap magmatism (Sobolev et al., 2009) constrains the melt stability domain between the 1600 and 1500 °C geotherms (Fig. 6 in the cited paper), which generally agrees with the model of a plume head by Dobretsov et al. (2001). The latter model, however, predicts that melt accumulates in the plume head but fractionates in the chamber as a result of convection and cooling (Dobretsov et al., 2001), unlike the more sophisticated model of Sobolev et al. (2009) with transport of carbonate-bearing eclogite entrained by plumes from old subduction zones. Nevertheless, the very modeling of interactions between plume melts and peridotite (or eclogite) is worth attention.

The cited paper of Sobolev et al. (2009) co-authored by two brothers Alexander and Stepan Sobolev continues the family tradition. Vladimir S. Sobolev, together with his other son, Nikolay, were among the first to formulate the idea that continental crust results from recycling of eclogitic oceanic crust in subduction zones unlike the oceanic crust production in mid-ocean ridges (Sobolev and Sobolev, 1975). Another pioneering idea of V. Sobolev concerns involvement of deep-seated hydrocarbons and CO_2 in diamond formation (Sobolev, 1960). Another pioneering study of the family (Sobolev et al., 1966), with participation of Eugene Sobolev, one of Vladimir's elder sons, showed that diamonds from the first discovered ecolgitic xenolith had the same amount of nitrogen (Bobrievich et al., 1959) as those from the Mir kimberlite (Yakutia) (Sobolev et al., 1966).

The overview by Touret and Huisenga (2020) focuses on supercontinents which formed on the post-Archean Earth. The supercontinents, especially Gondwana and Rodinia, which amalgamated in the Neoproterozoic to late Cambrian, were sutured by orogenic belts formed in high-temperature metamorphic settings. At the final stage of amalgamation, the lower continental crust heated up to magmatic temperatures of 900 to >1000°, which took from 10 myr in young short-lived orogens to as long as 150 myr in Precambrian (Gondwana) and Neoproterozoic (Rodinia) long-lived belts.

Ultrahigh-temperature granulite samples from those orogens bear fluid inclusions of the same type, with high-density CO_2 and concentrated saline solutions. Judging by abundant preserved fluid inclusions (especially high-density CO_2) and widespread secondary effects, the fluids were expelled from the lower crust to higher crustal levels at the end of the high-grade metamorphic event and caused regional-scale feldsparization, albitization, and scapolitization. Those processes were accompanied by deformation that produced shear zones with quartz-carbonate (oxidized) and graphite (reduced) veins. Most of CO_2 and brine inclusions, with few exceptions due to local effects, originated from carbonatite melts generated by melting of metasomatized mantle.

The problem of continent breakup was also among the subjects of the opening overview by Dobretsov (2020) which, like many previous studies, highlighted the effect of plumes, as sources of alkali-basaltic and carbonatite melts, at least in the breakup of Rodinia and Pangea. Plume magmatism played an important role in the India-Eurasia collision and related processes, namely, 26–10 Ma alkaline magmatism in the southern and eastern Tibet (Gao et al., 2007; Lai et al., 2014; Guillot et al., 2019) and carbonatite magmatism of 40–31 Ma Sichuan (Xu et al., 2003) and 23–7 Ma Qiling (Xu et al., 2014) provinces. As it was noted by Guillot et al. (2019) at the commemorative V.S. Sobolev conference, the occurrences of carbonatites are more common to rifting conditions and related to deep plume activity, such as Ol Doinyo Lengai in Tanzania or Kaiserstuhl in Germany. The carbonatite and kamafugite associations at the borders of the Tibetan Plateau have been attributed to the activity of mantle plumes (Ernst and Buchan, 2002), but the Sichuan carbonatites more likely originated from lithospheric mantle intensely metasomatized by marine subducted sediments (Guillot et al., 2019).

The heating of the lower crust by intrusions of carbonatite magma and formation of high-temperature granulites during amalgamation of supercontinents may be related to the activity of lower mantle plumes, but the problem remains controversial (Dobretsov et al., 1996; Ernst and Buchan, 2002; Guillot et al., 2019; Touret and Huisenga, 2020) and open to discussions.

Another paper from the first part in the volume deals with high-pressure metamorphism related to subduction (Fedkin, 2020), for the case of eclogites from the Maksyutov metamorphic complex. High-pressure metamorphism, which was mapped on a large scale in the USSR (Sobolev et al., 1967) and Europe in the 1960s, was among the multiple research interests of V.S. Sobolev. Proceeding from geothermometry and geobarometry data, Fedkin (2020) distinguishes four events of progressive metamorphism in the Maksyutov complex, with the pressure and temperature conditions and possible ages of 800–910 °C, 2.5–3.5 GPa, and 533 Ma (1); 540–790 °C, 2.0–3.5 GPa, and 385–393 Ma (2); 410–680 °C, 1.1–2.5 GPa, and 345–370 Ma (3); and 410–550 °C, 1.0–1.2 GPa, and 315–335 Ma (4). They plot a single P–T–t trend similar to that of ultrahigh pressures in the Kokchetav belt, Kazakhstan (Fig. 1). The time constraints of the events were obtained by correlating data from more than ten publications (from 1997 through 2015) with results of thermomechanic modeling, which revealed several episodes of exhumation.

An ultrahigh pressure setting of the Maksyutov metamorphism is indicated by the presence of quartz pseudomorphs after coesite described previously (Chesnokov and Popov, 1965; Dobretsov and Dobretsova, 1988) and cubic graphite grains after diamond and diamond microinclusions in garnet found later (Leech and Ernst, 1998), which record the 2.7–3.5 GPa and 600–700 °C conditions on early stage during mineral formation. These results are consistent with data on eclogites from the Shubino, Novosimbirka and Karayanovo areas. The highest values were obtained for samples 219 and 271: 660–945 °C at 3.6 GPa and 600–845 °C at 3.5 GPa. However, the temperature values may be overestimated as the Maksyutov complex lacks melting signatures; the range 660–730 °C appears more reasonable and agrees with the results of Valizer et al. (2013) cited in (Fed'kin, 2020).

The 533 Ma age of the earliest metamorphic event in the Maksyutov complex is tentative and may represent the age of the protolith (Dobretsov et al., 1996). Better time constraints were obtained for eclogites and diamond-bearing rocks of the Kokchetav belt, which is a tectonic mélange of imbricate thrusts and blocks exhumed from different parts of a subduction zone (Barchi, Kumdy-Kul, Enbek-Berlyk, and Kulet), each having its specific *P–T* history (Claoue-Long et al., 1991; Shatsky et al., 1999; Schertl and Sobolev, 2013). The composite *P–T* evolution curve for the Kokchetav rocks shares many features of similarity with that for the Maksyutov complex. Both complexes underwent multi-stage metamorphism that records the evolution of different parts in the subduction zone, with different exhumation ages of metamorphic blocks.

Aranovich et al. (2020) discuss generation and evolution of magma in mid-ocean ridges, with reference to zircon as a petrogenetic tracer of processes in the lower oceanic crust. Magmatic zircons in oceanic gabbro formed from fractionating parent melts in a mid-ocean ridge setting, rather than crystallizing instantaneously. This crystallization style is recorded in morphological diversity of zircons and in variations of their mineral chemistry. Fractional crystallization in a cooling melt is indicated by rimward Hf increase, often concurrent with increase in the (U + Th) and (Y + P) contents (Aranovich et al., 2020 and references therein). The authors suggest using a geothermometer based on Zr and Hf partitioning between zircon and rock.

A similar tendency shows up, though less distinctly, in magmatic zircons from oceanic plagiogranites. These zircons have narrower crystallization intervals and are more depleted in REE than those from gabbro, which supports the idea that plagiogranite formed by partial melting of gabbro with participation of saline fluids derived from seawater (Aranovich et al., 2020).

Zircons can recrystallize as a result of dissolution-precipitation reactions. The respective sites contain microinclusions of xenotyme, oxide phases, or U and Th silicates and baddeleyite ZrO_2, apparently due to the effect of reduced and alkaline fluids (Aranovich et al., 2020). However, zircon cannot crystallize in the presence of olivine (Dobretsov et al., 2019) and thus forms only in fractionated olivine-free gabbro rather than at the early crystallization stage.

Two other petrological papers deal with problems of magmatism. Experiments by Perchuk et al. (2020) studied melting of material close to the average composition of global subducting sediments (GlOSS) at the *P–T* conditions of 750–900 °C and 2.9 GPa similar to those in real subduction zones. The results have important implications for subduction magmatism. Two series of experiments were conducted in unsealed and sealed capsules and both yielded garnet, carbonate, kyanite, SiO_2 phases, and phengite. However, omphacite formed in all runs with unsealed capsules but was restricted to the subsolidus conditions (at 750 °C) in the case of sealed capsules.

Thermodynamic calculations for the H_2O + GLOSS mixture in a closed system fit well the experimental data in the subsolidus domain and show decreasing omphacite percentages upon melting, which correspond to the effect of fluid pressure increase in sealed capsules. They also show complete decomposition of carbonates in the slab during hot subduction and thus agree with field data but contradict the experiments (Perchuk et al., 2020). Another difference from the field evidence noted by the authors consists in phengite being the only hydrous phase, whereas natural suprasubduction felsic volcanics mainly contain biotite and amphibole (Dobretsov, 2010; Van Keken et al., 2011). This discrepancy is explained (Perchuk et al., 2020) by the fact that biotite and amphibole crystallize at pressures below 2.5 GPa, as it was confirmed experimentally (Hermann and Spandler, 2008). The absence of phengite phenocrysts from felsic island arc magmas may have several reasons (Perchuk et al., 2020): (i) magma generation occurred at a pressure below 2.5 GPa; (ii) phengite phenocrysts dissolved in the ascending magma; and (iii) phengite dissolved in the magma upon interaction with peridotite or upon mixing with other melts.

Two latter scenarios may also account for the absence of carbonate phenocrysts in island arc lavas, though they are abundant in the run products. However, the discussion will continue till the discovery of pseudomorphs after carbonate or phengite phenocrysts or their relicts, or some other evidence for large-scale participation of carbonates or phengite in the formation of island arc lavas.

Another experimental study of magmatism was authored by Persikov (2020) and reveals new viscosity patterns in felsic, intermediate, and mafic liquidus-free hydrous magmas in a large range of *P–T* parameters and crust depths from 1 to 30 km. The viscosity of magmas of different compositions is calculated using a structural chemical model. The resulting patterns (Persikov, 2020) confirm the idea of V. Sobolev, P. Escola, and others that highly viscous felsic melts predominate in intrusions (granite plutons and dacite extrusive domes) while low-viscosity basaltic melts are mainly effusive and also form early Precambrian ultramafic komatiites.

However, viscosity of melts depends on water contents no less than on their composition, which leads to a major exception: andesite and dacite (rather than basalt) lavas predominate in subduction zones where magma generation occurs at high water pressures. Felsic magmas in these areas are prone to gas explosion with formation of ash clouds which can travel long distances up to 1000 km in air and continue flowing as ignimbrites after the fallout.

Discussions at the international conference devoted to the 110th anniversary of V. Sobolev (Novosibirsk, 2018) and in this volume include the issue of melt inclusions in minerals (Portnyagin et al., 2019; Sobolev et al., 2019; Tobelko et al. 2019; Mironov et al., 2020). It was V. Sobolev who initiated this line of research in the USSR and led the academic school of thought on magmatic inclusions in minerals which became internationally reputed.

The publications of the second thematic part (experiments and mineralogy) begin with the paper of Mironov et al. (2020) on the pressure of volatiles during crystallization of island arc magmas inferred from data on melt inclusions. Melt and/or fluid inclusions in phenocrysts of early phases have implications for CO_2 contents in parent melts because they release almost all CO_2 at low pressures. Mironov et al. (2020) suggest a new method for estimating CO_2 density in the fluid phase of melt inclusions by Raman spectroscopy. This is a pioneering approach for Russia, though it was reported earlier in some international publications (e.g., Harley et al., 2014; Aster et al., 2016). It allowed constraints on the crystallization conditions of parent magmas at Karymsky volcano in Kamchatka: >0.7 GPa pressure of the CO_2–H_2O fluid at depths more than 25 km (Mironov et al., 2020). The results agree with seismic data (e.g., Zobin et al., 2003).

The versatile research interests of V. Sobolev extended to the formation of Norilsk-type complex-ore sulfide deposits which he attributed to magmatism. This subject is treated in the paper of Ariskin et al. (2020) for the case of PGE sulfide mineralization in troctolites of the Yoko-Dovyren layered intrusion in the northern Baikal region. Detailed data on major-element compositions of sulfide phases prove their magmatic origin and provide evidence for spatial dispersal in the course of solidification of troctolite cumulates.

V. Sobolev paid much attention to the geology and mineralogy of diamonds. Three papers of the Special Issue report experimental results on mantle *P–T* parameters and analytical data on natural diamonds and their mineral assemblages (Bataleva et al., 2020; Sobolev et al., 2020; Sokol et al., 2020). The stability conditions of natural carbonates, fluid regime in reduced mantle, and relations between diamonds and mineral or fluid inclusions they host are important in reconstructions of the global carbon cycle.

Experiments reported by Bataleva et al. (2020) were the first to reproduce decarbonation reactions at mantle-crust interactions associated with the formation of Mg,Fe-garnets and a CO_2 fluid in a large upper mantle *P–T* range. The experiments were performed on a split-sphere multi-anvil apparatus with a specially designed buffered high-pressure cell using a hematite container that prevents hydrogen leakage from Pt capsules. The results demonstrate that decarbonation occurs at 1100 ± 20 °C (3.0 GPa), 1150 ± 20 °C (6.3 GPa) and 1400 ± 20 °C (7.5 GPa) in the $MgCO_3$–SiO_2–Al_2O_3 system and at 1000 ± 20 °C (3.0 GPa), 1150 ± 20 °C (6.3 GPa) and 1400 ± 20 °C (7.5 GPa) in the (Mg, Fe) CO_3–SiO_2–Al_2O_3 system. The experimentally reproduced reactions with formation of pyrope+CO_2 or pyrope-almandine + CO_2 assemblages shift toward temperatures 50–150 °C lower than the calculated values. As shown by the results, Mg and Fe carbonates react with oxides between 1000 and 1250 °C at depths 90–190 km and at 1400 °C around 225 km.

Sokol et al. (2020) summarize experimental results on compositions of quenched fluids correlated with data on fluid inclusions in natural diamonds and provide an ample list of references, mostly published in 2010 through 2019. The experimental data from model systems and analyses of hydrocarbon inclusions in natural diamonds allow insights into the upper mantle fluid regime. Various hydrocarbons, mainly light alkanes and oxygenated species, may form in the mantle from inorganic substances, with participation of N-, S-, and Cl-bearing fluids. Carboxylic acids and other oxygenated hydrocarbons can be stable in H_2O-N_2-CO_2 fluids, in equilibrium with carbonated peridotite. Future experiments may address changes in fluid components of inclusions during transport to the surface, as well as causes of the difference in relative percentages of methane, light alkanes, oxygenated HCs, and water in the analyzed systems.

Sobolev et al. (2020) measured orientations of seventy six olivine, pyrope, and magnesiochromite inclusions in sixteen diamond samples from primary diamond deposits in Yakutia. The novelty of the studies consists in a special approach to the choice of kimberlite samples containing peridotitic pyrope and magnesiochromite inclusions besides the common olivine. No inclusions had orientations fitting the epitaxial criterion, in both new and previous (2014–2019) experiments; quasi-regular orientations were restricted to magnesiochromite from three diamonds. Significant correlation of carbon isotope composition and the mineral chemistry of peridotitic and eclogitic diamond inclusions in the absence of correlation with other properties may be interpreted as a geochemical feature. On the other hand, syngenetic and protogeneic inclusions may coexist in a single diamond, judging by a wealth of evidence on complex growth history of diamonds and locally observed large variations in the composition of mineral inclusions in different zones. This idea agrees with findings of kimberlites that contain diamondiferous peridotite and eclogite xenoliths in which all diamond was enclosed in garnet or olivine. Heavy hydrocarbons from pentane (C_5H_{10}) to hexadecane ($C_{16}H_{32}$) reach high relative percentages in fluid inclusions from kimberlite-hosted and placer diamonds, as well as in pyrope and olivine from diamondiferous peridotite xenoliths (Sobolev et al., 2018, 2019).

V. Sobolev was also an expert in identification of rare and unique mineral phases. This line of research is presented in the Special Issue by the paper of Pekov et al. (2020)

who describe unique mineralization of fumarolic systems in Tolbachik volcano, Kamchatka. The extremely diverse mineral assemblages, which count up to 350 mineral species including 123 minerals first discovered in the Tolbachic fumarolas, result from an unusual combination of high temperatures, low pressures, high oxygen volatility, and particular chemistry of volcanic gases.

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