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# EXPERIMENTAL STUDY OF THE SYSTEM ALKALI BASALT — — WATER UP TO PRESSURE 20 KBAR IN RESPECT TO ESTIMATION OF H<sub>2</sub>O CONTENT IN THE ORIGINAL MAGMAS BENEATH ISLAND ARCS

(Figs. 9)

**Abstract:** The natural alkali basalt of the following composition has been chosen: SiO<sub>2</sub> — 49.73; TiO<sub>2</sub> — 2.10; Al<sub>2</sub>O<sub>3</sub> — 15.82; FeO — 9.57; MgO — 6.41; MnO — 0.16; CaO — 9.30; Na<sub>2</sub>O — 3.45; K<sub>2</sub>O — 1.34; P<sub>2</sub>O<sub>5</sub> — 0.33; total — 99.05. The experiments were conducted in the isobaric sections at 10, 15 and 20 kbar using piston-cylinder apparatus with 1/2 and 3/4 inch chambers. 5 kbar section and the position of the water saturated liquidus onto the P-T plan up to 5 kbar have been studied using a gas vessel. At P = 1 atm. and T = 1205 °C the liquidus has been determined by a loop method in the high-temperature furnace with  $f_{O_2} = 10^{-8}$  controlled by the given ratio H<sub>2</sub>/CO<sub>2</sub>. Dry liquidus is studied by the reversal method in the graphite tubes sealed in platinum capsules. At pressures below 10 ± 0.5 kbar olivin (Ol) is mineral of liquidus and above 10 kbar — clinopyroxene (Cpx). With the Ni—NiO buffer in the nickel capsules Ol also is mineral of the water saturated liquidus up to P = 5 kbar. Above 10 kbar Cpx is stable at the liquidus, whatever the water content in the system (N<sub>H<sub>2</sub>O</sub><sup>L</sup>) is. Change of minerals at liquidus reflect a change in the melt structure these minerals crystallized from, with decreasing T, N<sub>H<sub>2</sub>O</sub><sup>L</sup> or increasing the total pressure P<sub>s</sub>. This conclusion follows from the data on the H<sub>2</sub>O solubility in the melt at the water saturated liquidus: (T °C/P, kbar/wt. %): 1015/1/3; 1060/2.9/6.3; 1035/5/8.2; 1018/10/10.5; 1015/11/19.8; 1009/15/20.2 and 1008/20/21.4. Plotting these data onto the P—N<sub>H<sub>2</sub>O</sub><sup>L</sup> plan the inflection of water content is appeared over 10—11 kbar range. This inflection is supported to be due to phase transition of orthosilicate clusters in the melt into the metasilicate ones. A projection of liquidus surface onto P-T plane is deduced on the base of experimental data, and the water contents in the melts generated in the upper mantle beneath the Aleutian island arc and Western Hoashu in Japan are evaluated.

**Резюме:** Для экспериментов был выбран образец щелочного базальта следующего состава: SiO<sub>2</sub> — 49.73; TiO<sub>2</sub> — 2.10; Al<sub>2</sub>O<sub>3</sub> — 15.82; FeO — 9.57; MgO — 6.41; MnO — 0.16; CaO — 9.30; Na<sub>2</sub>O — 3.45; K<sub>2</sub>O — 1.34; P<sub>2</sub>O<sub>5</sub> — 0.33; сумма 99.05. Исследования проводились в изобарических сечениях при 10, 15 и 20 кбар на аппаратах цилиндр-поршень, в камерах 1/2 и 3/4 дюйма; сечение 5 кбар, а также положение водонасыщенного ликвидуса на РТ диаграмме до 5 кбар изучено в газовой бомбе. Ликвидус при P=1 атм и 1205 °C определен методом

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**Symbols:** T — temperature °C, P<sub>H<sub>2</sub>O</sub> — water pressure, N<sub>H<sub>2</sub>O</sub><sup>Liq</sup> — water content at liquidus, Cpx — clinopyroxene, Am — amphibole, Ol — olivine.

петли в высокотемпературной печи при  $f_{O_2} = 10^{-8}$ , заданным соотношением  $H_2/CO_2$ . Сухой ликвидус изучен подходом с двух сторон в графитовых вкладышах, запечатанных в платиновые ампулы. До 10—0.5 кбар минералом ликвидуса является оливин (Ol), а выше — клинопироксен (Cpx). На буфере Ni-NiO в никелевых ампулах удалось сохранить Ol в качестве минерала водонасыщенного ликвидуса до  $P = 5$  кбар. Выше 10 кбар Cpx стабильно удерживается на ликвидусе при любом содержании воды в системе  $N_{H_2O}^L$ . Смена минералов ликвидуса отражает изменение структуры расплава, из которого эти минералы выпадают при снижении  $T$ ,  $H_2O$  или же увеличении общего давления ( $Ps$ ). Этот вывод вытекает из данных по растворимости  $H_2O$  в расплаве на водонасыщенном ликвидусе. Её содержание возрастает следующим образом ( $T^\circ C/P$ , кб/вес. %): 1015°/1/3, 1060/2.9/6.3, 1035/5/8.2; 1018/10/10.5; 1015/11/19.8; 1009/15/20.2 и 1008/20/21.4. При нанесении этих данных на диаграмму  $P-N_{H_2O}^L$  обнаруживается скачок в растворимости воды в расплаве между 10 и 11 кбар, обусловленный, как предполагается, фазовым переходом ортосиликатных кластеров в метасиликатные. На основе полученных экспериментальных данных выведена проекция поверхности ликвидуса базальта на плоскость  $P-T$  и произведена оценка содержаний  $H_2O$  в расплавах, генерируемых в верхней мантии под Алеутской островной дугой и под Западной частью о. Хонсю в Японии.

The data on the heat flow distribution and thermal structures of the mantle diapirs beneath marginal seas in general and the Japanese sea in particular show the high level location of geotherms in these parts of lithosphere. The crust thickness there accounts for only half on the normal continental crust mainly due to granite layer decrease. The asthenosphere roof is located at a depth of about 100 km under very high temperature conditions (1500—1600 °C). Beneath the island arcs the zone of partial melting of the mantle garnet lherzolites remains either at the same level or is raised up to 35—40 km. But whatever the depth of the asthenosphere roof with the 1100—1200 °C isotherms is sufficiently close to the crust surface.

Fig. 1 shows two geophysical cross-sections through the Earth crust and the upper mantle beneath the Sea of Japan and Island Honshu on the one hand, and the Aleutian island arc and the Commander basin, on the other. Beneath the Sea of Japan the roof of asthenospheric lens is located at a depth of about 100 km, through the Earth crust and the upper mantle basement of Western Honshu is not so dense at the same level as that under the sea.

As is known, the territory of Western Japan continues to be a zone of active seismicity and volcanism (andesites, andesite-basalts and alkali basalts). One would think, in this zone isotherms should be-raised closer to the Earth surface, but actually they are located at the great depth; so temperature in the area with partial melting of garnet harzburgites and lherzolites is only about 1200 °C. It corresponds to the liquidus of the dry basalt at  $P = 1$  atm. But recent experiments at  $P = 35$  kbar (see Fig. 2) have shown that this temperature should be no less than 1400 °C. In the pressure range 15—20 kbar the temperature estimates of the garnet lherzolite partial melting are 1100 °C beneath the Aleutian island arc and are to be about 1300 °C for the anhydrous system.

Thus, geophysical data have shown that temperature estimates of the partial melting of garnet lherzolites beneath the marginal seas and island arcs within the depth range of 50—100 km are approximately by 200 °C lower of the alkali basalt dry liquidus determined experimentally. These data contradict with a widespread opinion that basalts in the upper mantle generate without fluids and water, in particular. Due to this opinion the system basalt — water has been poorly studied for many years. For example, there are practically no

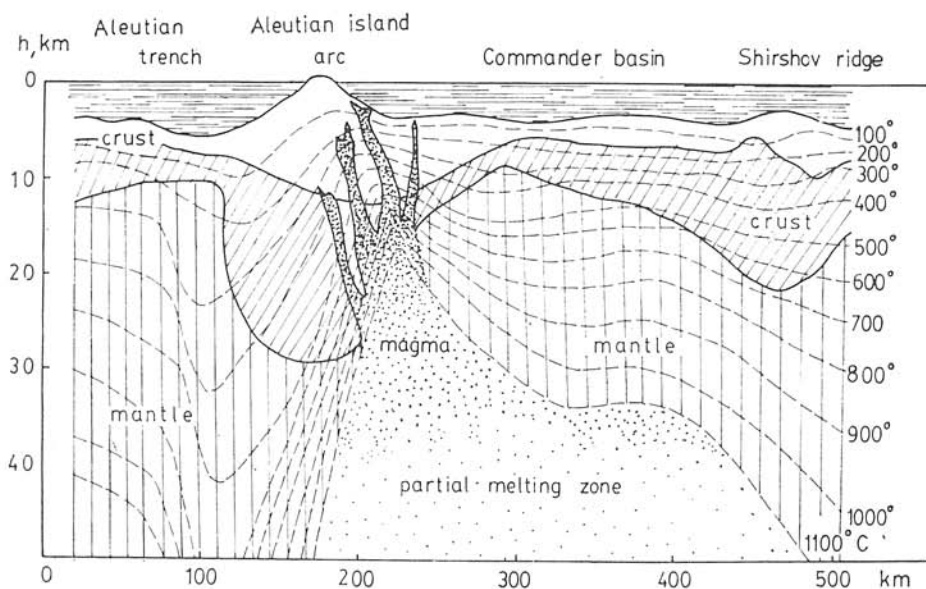
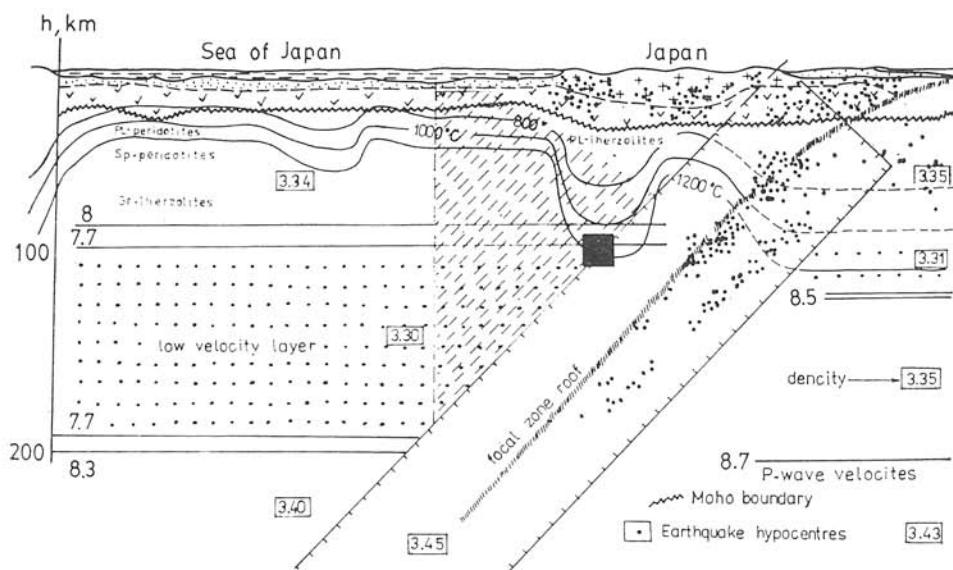


Fig. 1. Sketches of the lithosphere construction beneath the Sea of Japan and Honshu Island (after Родников и др., 1982) and beneath the Aleutian island arc (after Смирнов-Сугробов, 1979).

correct data on the system basalt — water above 10 kbar. The present paper is to study this system and estimate the water content at any point of the upper mantle melting beneath the marginal seas and island arcs.

We have studied the system alkali basalt — water in the pressure range from 1 atm. to 20 kbar. The starting material is a basalt (from Kuznetsk Ala Tau) with a composition similar to the average alkali basalt of the Japan Sea bottom.

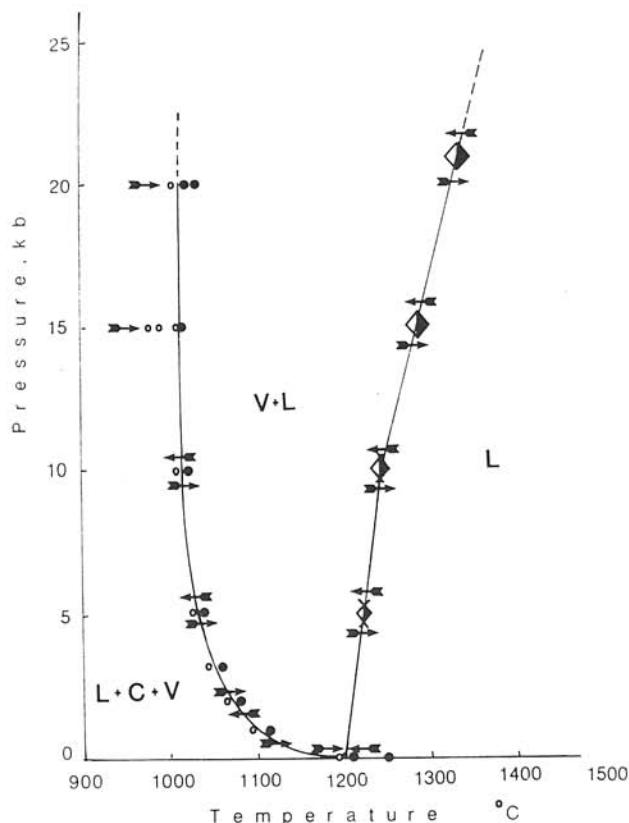


Fig. 2. Dry and water-saturated liquids of alkali basalt plotted onto P-T plane.

The basalt used for experiments contains about 20% phenocrysts of Cpx, Ol and the cryptoperthite Fsp. A medium-grained groundmass consists of labradorite, clinopyroxene, ilmenite and a small amount of feldspathic glass. Olivin is rimmed with clinopyroxene. Basalt was ground to  $\sim 10$  microns in a mechanical mortar. One part of this powder was dried at 1100 °C and another one melted at 1300 °C and  $f_{O_2} = 10^{-8}$  atm. in a silicon-carbide quenching furnace with the controlled  $O_2$  fugacity during 20–30 min.

One-atmosphere runs were conducted in the same furnace at  $f_{O_2}$  corresponding to the Ni-NiO buffer with different run durations. To find the liquidus

a "loop method" was used. The experiments over the range 1 to 5 kbar have been carried out in gas vessels using the above mentioned buffer, but with nickel external and silver-palladium internal capsules ( $\text{Ag}_{70}\text{Pd}_{30}$ ).

The experiments above 10 kbar have been conducted in a piston-cylinder apparatus using "piston out" procedure. The 1/2 and 3/4 inch assemblies consistent of glass, talc, graphite heater as well as internal cylinders and a tube from soft ceramics have been, therewith, used. The accuracy of the tempera-

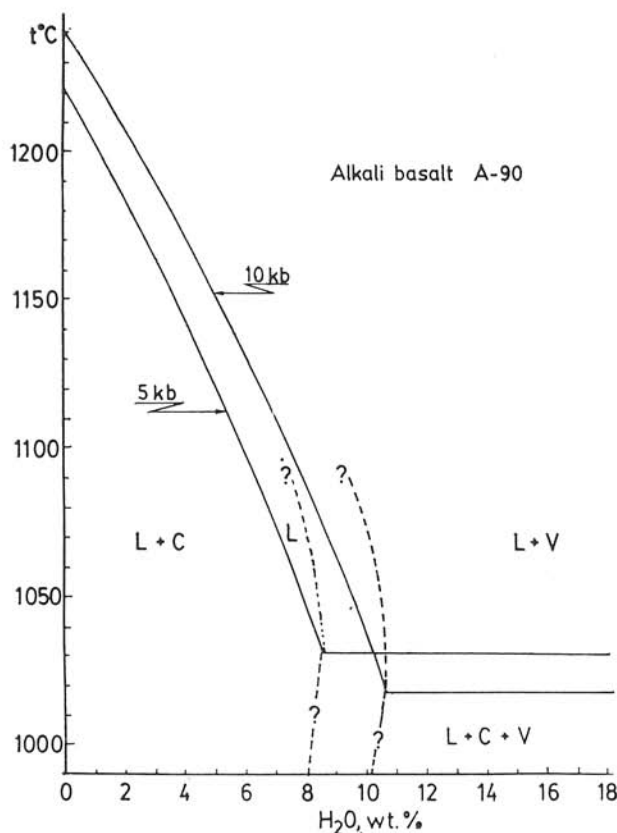


Fig. 3. Isobaric sections 5 and 10 kbar for liquids of alkali basalt plotted into the P-N<sup>Liq</sup><sub>H<sub>2</sub>O</sub> plane.

ture regulation and pressure estimates was within  $\pm 2^{\circ}\text{C}$  and  $\pm 0.2$  kbar, respectively. The experiments were conducted in the silver-palladium capsules ( $\text{Ag}_{70}\text{Pd}_{30}$ ) with an inner diameter of 1.5 mm. Weighting of the basalt powder was made with a high precise balance (Mettler H51AR). Run duration varied within 1–16.5 hours. Any Fe-losses into the capsule walls during the run were not detected by microprobe.

The method of appearance or disappearance of crystals was used to determine the liquidus position in the isobaric sections of the basalt-water-temperature-pressure diagram. This method turned out to be rather efficient for studying all the isobars with water content up to 5 wt. % as well as for the system under consideration. Several isobaric sections, i.e. 3, 5 and 10 kbar have been studied by this method. Two of them are shown in this Fig. 3. At pressures above 10 kbar Cpx is the liquidus mineral whose crystallization presents some difficulty if the water content exceeds 5 wt. %. Cpx does not crystallize in the stability field below liquidi. Due to very sluggish crystallization of clinopyroxene from the melt it was difficult to determine position of the liquidus by re-

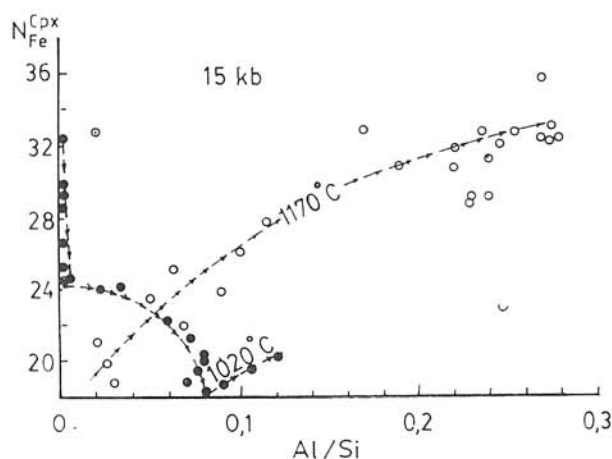


Fig. 4. Chemical zoning developed in the liquidus Cpx during the runs at 15 kbar in the system basalt — water. Arrows show the Cpx crystal growth path from cores towards margins at 1020° and 1170°C. A-90 is a starting composition of Cpx overgrown by new zones during the run.

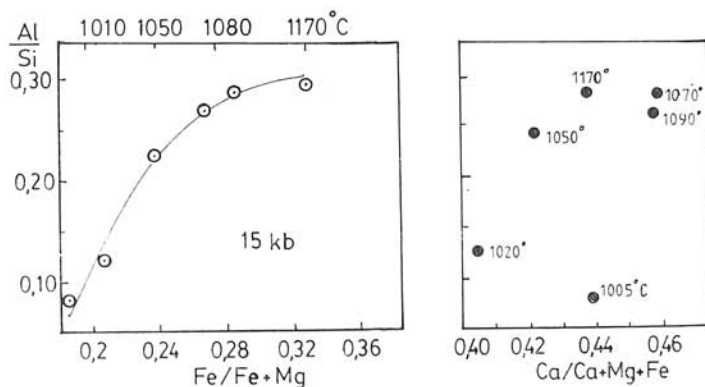


Fig. 5. Correlation between compositional parameters of Cpx at liquidus of the system alkali basalt — water. The  $\text{FeAl}_2\text{SiO}_6$  content in Cpx increases with temperature. Diagram is based on the numerous microprobe data.

versible method. Thus, the liquids were estimated by dissolution of the clinopyroxene crystals with the grain zoning control (Пeрчyк, 1983 b).

Let us consider this procedure in detail. The basalt powder with weighted water content has been sealed in a capsule and heated under experimental conditions over 10 kbar. Primary olivine crystals disappeared, Cpx is overgrown by new compositional zones. Approaching liquidus the Cpx zoning reduced and completely disappeared at the liquidus, Cpx, therewith, being resorbed. 2—3 Cpx relics in the glass were indicators of the liquidus.

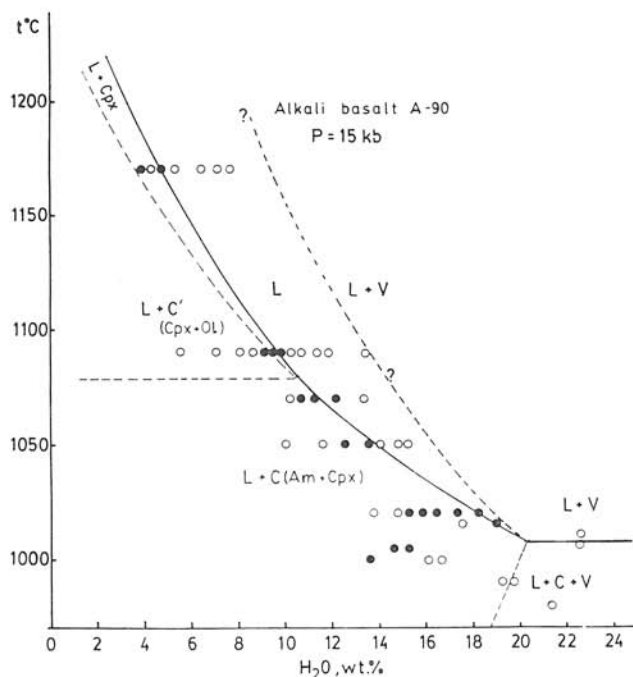


Fig. 6. Phase relationships in the system alkali basalt — water at 15 kbar. Solid circles belong to the runs with products analysed by microprobe. Liquidus has been achieved from the low temperature side.

Diagram of Fig. 4 gives evolution of the Cpx crystallization for the 15 kbar isobaric section in 2 runs at 1020° and 1170 °C. You can see that in the run at 1020 °C Cpx relics are included in Cpx grains of a new chemical composition. The alumina and iron contents, thereby, decrease at the first stage. Then, at the point of  $Di_{80-75}Hed_{20-25}$  depending on temperature the alumina content and, subsequently, ferrochromite in Cpx increase. The higher the temperature, the greater the  $FeAl_2SiO_6$  content in the Cpx rims below liquidus. It is clear from the  $(Al/Si) - N_{Fe}^{Cpx}$  diagram at  $P = 15$  kbar (see Fig. 5) where the Cpx composition is regularly changed showing the stability limit of the mineral in the melt below liquidus. Thus, the method developed is efficient enough

to be allied for determination of the liquidus surface in the system basalt — water in the P-T coordinates.

Detailed study of the 15 kbar section is presented in Fig. 6. Solid circles belong to the run products, i.e. glass and minerals analysed by microprobe. Hornblende as well as Cpx appear near the water-saturated liquidus. The molar percent of Mg in Hb varies from 23 to 28. At 1090 °C olivine with  $N_{Mg} = 82.5$  appears along with Cpx.

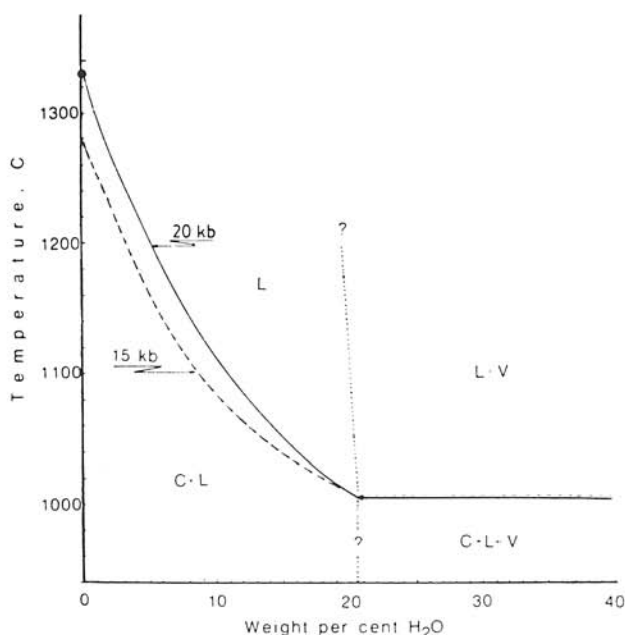


Fig. 7. Phase relationships in the system alkali basalt — water at 20 kbar. Liquidus has been achieved from the low temperature side. The 15 kbar liquidus (dashed line) is shown for comparison.

Diagram in Fig. 7 shows a section of the system at 30 kbar. The liquidus curve at 20 kbar is compared with liquidus at 15 kbar. Shift of the invariant points is seen to be negligible, only by  $\sim 1$  wt. %  $H_2O$ . However, comparing the invariant points at 15 and 10 kbar we can see great differences in water contents at the water-saturated liquid: 10 and 20 wt. %, respectively. We have additionally studied positions of the invariant points at 12.5 and 11 kbar. The water content at pressure of 11 kbar turned out to be 19.8 wt. %, i.e. the water solubility in the water-saturated melt increases sharply within the pressure range 10–11 kbar (Fig. 8). We consider this phenomenon illustrated by this diagrams as a result of the structural change in the melt at liquidus, i. e. with transition of orthosilicate clusters into the band (or schist) metasilicate ones.



The above change of water solubility in the basalt melt can be seen in this P-T diagram (Fig. 9) where isopleths are shifted towards the high temperature field. This diagram being the main purpose of our study shows a projection of the liquidus surface of the alkali basalt onto the P-T plane. It can be used for estimating the water content in the basalt melt at given P-T conditions.

Let us return to the beginning of our lecture where we based the importance of studying the system basalt — water at high pressures. On the basis of the

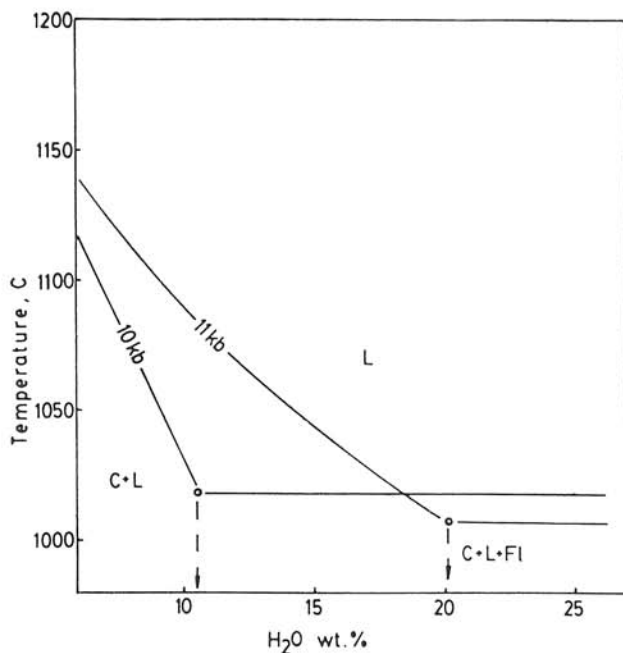


Fig. 8. Liquidi of the system alkali basalt — water at 10 and 11 kbar plotted onto the P-N<sub>Liq</sub> plane. Positions of invariant points show large differences in solubility of water in the melt at liquidi.

geophysical section constructed through the Aleutian island arcs and Japan we can estimate the water content in a melt in the partial melting zone of garnet lherzolites at 1200 °C and 20 kbar, 1100 °C and 16 kbar, respectively. Geotherms beneath these arcs are shown in Fig. 9. Using P-T conditions at the asthenosphere roof we may estimate the water contents in melts by intersection of geotherms with isopleths in this diagram (Fig. 9). They seem to be rather high, approximately 9 wt. %. These estimates are in good agreement with leucocratic composition of alkali basalts and andesite-basalts erupted in Western Japan and Aleutian islands. As is known from Youder's results the eutectic point in the system anorthite-diopside shifts towards anorthite with increasing water pressure resulting in the partial melting of the magmas poor in mafic components.

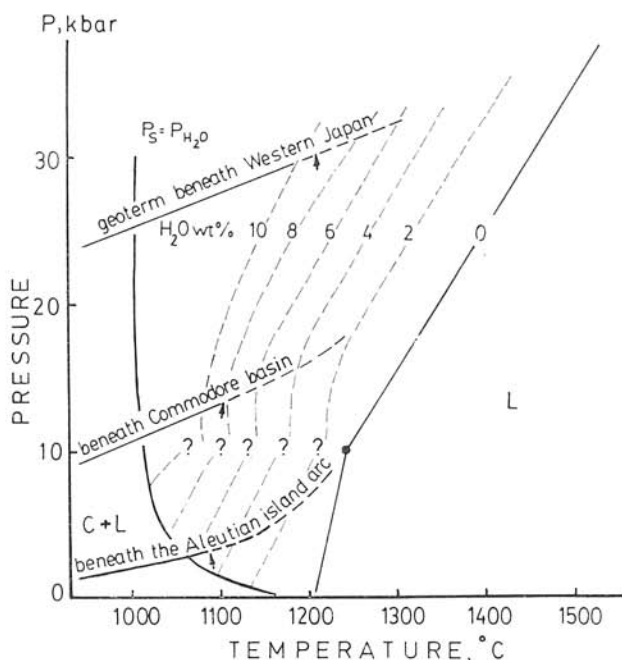


Fig. 9. Projection of the liquidus surface onto the P-T plane for the system alkali basalt — water. Arrows show the water contents in basalt magmas generated in the upper mantle beneath corresponding units marked. Dry liquidus after Перчук (1983 a).

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