GEOLOGICKÝ ZBORNÍK — GEOLOGICA CARPATHICA, 36, 3, BRATISLAVA, JUNE 1985,
Pp. 259—268

TOSHIMORE SEKINE* — PETER J. WYLLIE**

HYBRIDIZATION OF MAGMAS ABOVE SUBDUCTED OCEANIC CRUST

(Figs. 7)

Abstract: Hydrous siliceous melts rising from subducted oceanic crust may experience hybridization with overlying peridotite. Products of hybridization have been explored in the synthetic system $KAlSiO_4$—MgO—SiO_2—H_2O. The phase diagrams were used to interpret phase relationships determined at 30 kbar for mixtures of granite, peridotite, and H_2O. Results indicate that solution of peridotite in hydrous, H_2O-undersaturated granitic liquid at 900 °C, 30 kbar, causes only small changes in liquid composition, and precipitation of phlogopite-garnet-websterite. Additional experiments, set up with H_2O-undersaturated granite liquid in contact with solid peridotite at 30 kbar, 850—1050 °C, produced hybrid reaction zones containing orthopyroxene and clinopyroxene in all runs, and one or more of garnet, phlogopite, and quartz in some runs. The hybridization process in subduction zones could produce discrete rock bodies dominated by pyroxenite (without olivine); there is a prospect that potassium could become concentrated into phlogopite-rich rocks. The heterogeneous rock layer produced above subducted crust provides aqueous fluids expelled during hybridization, which rise to generate in overlying mantle the H_2O-undersaturated basic magnesian magma which is the probable parent of the calc-alkalic rock series erupted at the volcanic front.

Резюме: Кремниевые расплавы содержащие воду возникающие из океанической коры могли подвергнуться гибридизации с надлегающим перидотитом. Продукты гибридизации были изучены в синтетической системе $KAlSiO_4$-MgO-SiO_2-H_2O. Фазовые диаграммы были применены к интерпретации фазовых отношений определенных при давлении 30 кбар для смесей гранита, перидотита и воды. Результаты намечают, что раствор перидотита в H_2O-ненасыщенной гранитной жидкости содержащей воду при температуре 900 °C и давлении 30 кбар вызывает лишь маленькие изменения в составе жидкости и преципитацию флогопита-граната-вебстерита. Дополнительные эксперименты проведенные с H_2O-ненасыщенной гранитной жидкостью в соединении с твердым перидотитом при 30 кбар, 850—1050 °C создали гибридные зоны реакции, содержащие ортопироксен и клинопироксен во всех сериях, и одно или больше зон граната, флогопита и кварца в некоторых сериях. Процесс гибридизации в зонах субдукции может образовать тела отделенных пород с превосходством пироксенита (без оливина); существует перспектива, что калий может концентрироваться в породы богатые флогопитом. Слой гетерогенных пород образованный над поглоченной корой делает возможным выделение водных флюидов во время гибридизации, которая способствовала образованию в надлегающей мантии H_2O-ненасыщенной основной магнезиевой магмы, являющейся возможным источником серий известково-щелочных пород изверженных на вулканическом фронте.

---

* Dr. T. Sekine, Department of Earth Science, Monash University, Clayton, Victoria 3168, Australia.

** Dr. P. J. Wyllie, Division of Geological and Planetary Sciences. California Institute of Technology, Pasadena, California 91125.

Introduction

It was proposed a decade ago by Nichols—Ringwood (1973) that a critical stage in the petrogenesis of andesites and other calc-alkaline magmas involves hybridization. They suggested that hydrous siliceous melts resembling rhyodacites were generated in subducted oceanic crust, and then reacted with the overlying mantle peridotite, producing hybrid zones of olivine pyroxenite, at depths of 100—150 km. Diapirs of olivine pyroxenite would rise episodically from this zone, and subsequent partial melting of these wet, hybrid rocks would produce a wide range of calc-alkaline magmas, which may differentiate before eruption.

Much experimental effort has been directed towards determination of the products of partial fusion of the deep-seated source rocks of magmas. The melting relationships of peridotite, eclogite, amphibolite, and gabbro, as well as relevant synthetic model systems such as $CaO—MgO—Al_2O_3—SiO_2$, have been determined under various conditions. Similarly, the liquidus relationships of particular komatiites, basanites, basalts, and andesites have been studied with a view to relating them to specific source rocks, and identifying primary magmas. These forward and inverse approaches to petrogenesis were reviewed in detail by Wyllie et al. (1981). There has been very little experimental effort directed towards determination of the products of interactions among magmas, rocks, and aqueous fluids at mantle depths.

One way to investigate the products of hybridization is to model the phase relationships in synthetic silicate systems. Sekine — Wyllie (1982a) explored the data available in a system which includes representatives of (1) hydrous siliceous magma from the overlying mantle — the assemblage forsterite + enstatite in the system $Mg_2SiO_4—SiO_2—H_2O$. They extended their exploration in a series of systems with one additional component, $NaAlSiO_4$, $CaMgSi_2O_6$, $CaAl_2Si_2O_8$, and Al_2O_3 (Sekine — Wyllie, 1982b).

Another approach to the problem is to take whole-rock samples as starting materials. This approach involves too many components for graphical representation in standard phase diagrams. Sekine — Wyllie (1982c) investigated the phase fields intersected by mixtures of a natural granite and a natural peridotite, in the presence of H_2O, at 30 kbar pressure.

The equilibrium phase relationships in model and mixed-rock systems provide a basis for understanding hybridization processes in the mantle, but in the dynamic, subduction-zone environment hybrid rock masses may be produced by non-equilibrium, crystal fractionation processes. Sekine — Wyllie (1983) described experiments in which granite liquid is in contact with massive peridotite, in an attempt to simulate hydrous siliceous magma rising through mantle peridotite, and to determine the crystalline products produced by reaction at the boundaries between them.

Model system $KAlSiO_4–Mg_2SiO_4–SiO_2–H_2O$

The H_2O-saturated liquidus surface for the system $Mg_2SiO_4—KAlSiO_4—SiO_2$ at 20 kb is illustrated in Fig. 1. Liquidus fields for forsterite, enstatite, and quartz extend from the side $Mg_2SiO_4—SiO_2$ until they meet liquidus fields for phlogopite and sanidine. The field boundary between sanidine and quartz extending from the low-temperature eutectic on the side $KAlSiO_4$—SiO_2 terminates a very short distance into the system at the quaternary eutectic reaction at 680 °C. The low-temperature liquids occupy a limited area close to the side $KAlSiO_4$—SiO_2. The liquidus surface for phlogopite rises steeply from the eutectic and the boundaries limiting the fields for sanidine and quartz. The other two isobaric invariant liquid points are peritectics, representing incongruent melting reactions at 750 °C, and 1130 °C.

The three reactions are represented by three subsolidus compatibility triangles, Ph—Or—Qz, En—Ph—Qz, and Fo—En—Ph which are shown in Fig. 2. These sections illustrate the phase fields intersected by mixtures of Fo with the silicic compositions S_1, S_2 and S_3. Particularly noteworthy are the limited composition range of liquids through a wide temperature interval above the solidus near Ks—Qz, the wide extent of the fields for Ph + + L and Ph + Qz + L, and the increase in size of the field for En + L with increasing Qz/Or. The existence of crystalline Fo + En + Ph at the same temperatures as siliceous liquids is well displayed.

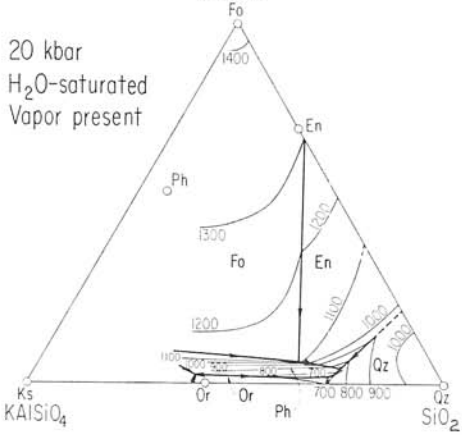

Fig. 1. H_2O-saturated liquidus for part of the system $KAlSiO_4$—Mg_2SiO_4—SiO_2—H_2O at 20 kbar, based on available experimental data, following Yoder (1976, p. 39).

Fig. 2 shows that, between 680 °C and 750 °C, addition of only a few per cent of Fo to molten or partially molten compositions S_1, S_2, and S_3 is sufficient to cause precipitation of phlogopite. There is a prominent phase field for Ph + L, and the field for Ph + Qz + L increases with increasing Qz/Or. Addition of Fo to the assemblage Ph + Qz + L continues reaction until all of the liquid is used up, producing Ph + Qz.

At temperatures between 750 °C and 1,130 °C, the main sequences of phase assemblages produced by adding Fo to liquids with compositions S_1, S_2, and S_3 are L, En + L or Ph + L, or En + Ph + L. When the liquid is used up, leaving the assemblage En + Ph, further addition of Fo produces the assemblage Fo + En + Ph without further reaction.

Phase relationships in the model system $KAlSiO_4$—Mg_2SiO_4—H_2O described above indicate that hybridization between hydrous siliceous melts and a simplified peridotite causes solution of the peridotite components with little change in liquid composition. Phlogopite is precipitated through a wide range of pressures, temperatures, and bulk compositions. Hybridization is not a simple mixing process.

The effects of CaO, Na_2O, and Al_2O_3 were examined by reviewing available data on phase relationships with additional components $CaMgSi_2O_6$, $NaAlSiO_4$, Al_2O_3, and $CaAl_2Si_2O_8$ (Sekine—Wyllie, 1982b). Addition of Na_2O and CaO changes the hybridization reactions by reducing the amount of phlogopite and by adding jadeitic clinopyroxene to the precipitation products. Addition of CaO and Al_2O_3 includes garnet among the precipitation products. The synthetic model systems appear to represent a good basis for extrapolation to the complex natural rock system.

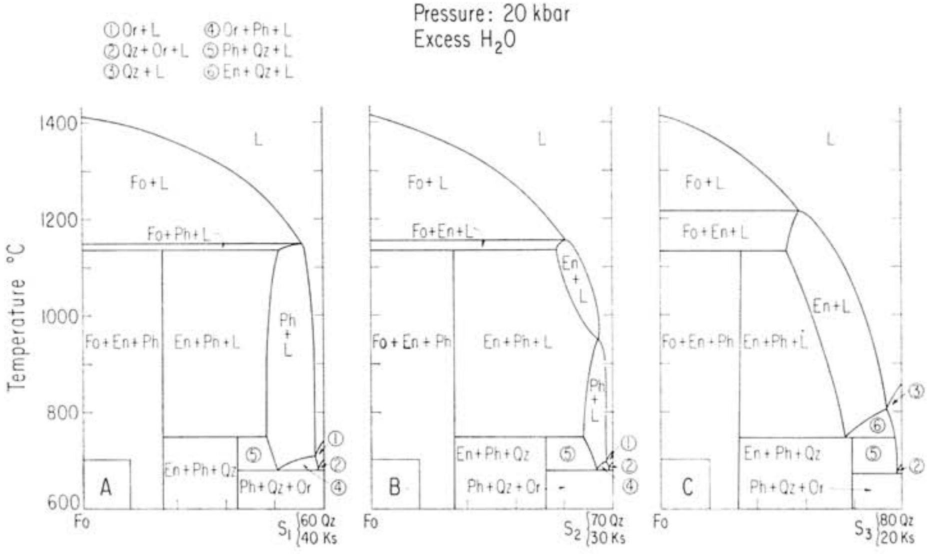

Fig. 2. Isobaric T-X sections for mixtures of Fo with S_1, S_2 and S_3 in the system $KAlSiO_4$—Mg_2SiO_4—SiO_2—H_2O at 20 kbar constructed from Fig. 1. Points S_1, S_2, and S_3 along the join Or—Qz represent compositions of silicous melts (Sekine—Wyllie, 1982a).

Equilibrium phase relations in granite-peridotite-H_2O

The starting materials were natural rocks with known geology, mineralogy, chemistry, and phase relationships. The crushed, mixed samples were sealed with water into gold capsules, and reacted at 30 kbar in piston-cylinder apparatus. Fig. 3 shows the estimated positions of field boundaries for the H_2O-saturated liquidus, and for the coexisting vaporus boundary.

Fig. 4 illustrates the distribution of the major phase volumes containing a small amount of vapor. Although few of the phase boundaries are closely defined by vapor-present runs, the distribution of phase volumes is unambiguous. The diagram is divided into three parts by the two vertical lines, corresponding to the boundaries separating olivine-bearing assemblages from pyroxenite, and subsolidus pyroxenite from partially melted pyroxenite. These three parts are occupied by subsolidus garnet-peridotite, garnet-pyroxenite, and quartz-garnet-pyroxenite. For each rock in the presence of H_2O there is a different solidus, with varying temperature caused by solid solutions in the mafic minerals. There are complex adjustments near granite, but these need not concern us.

The runs demonstrate that between the field for olivine extending from peridotite-H_2O, and the field for quartz extending from granite-H_2O, the liquidus is dominated by orthopyroxene. The orthopyroxene liquidus rises steeply from the low-temperature liquidus piercing point near the granite-H_2O side.

Glass analyses are plotted in Fig. 5, and compared with the four starting mixtures on the mixing line P—G, and with the average chemical variation of the calc-alkaline igneous series, B—G (Stern—Wyllie 1978; Sekine et al. 1981). All glasses measured in phase assemblages from mixtures M_3, M_2 and M_1 have compositions clustered towards the original granite, indicating that solution of the peridotite components in the liquid was limited.

Consider H_2O-undersatured granite liquid L at 900 °C and 30 kbar (Figs. 3 and 4). If this is emplaced within peridotite and allowed to reach equilibrium at constant pressure and temperature, the bulk composition of the

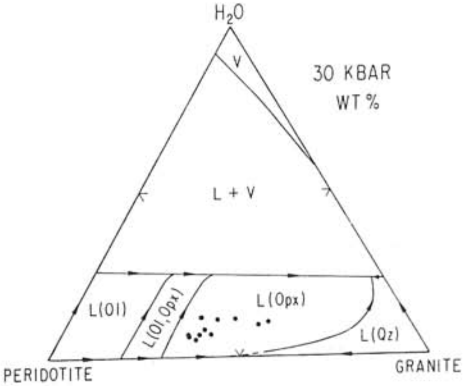

Fig. 3. Schematic liquidus phase relationships in the system peridotite-granite-H_2O at 30 kbar. Liquidus boundaries estimated from experiments cited by Sekine—Wyllie (1982c).

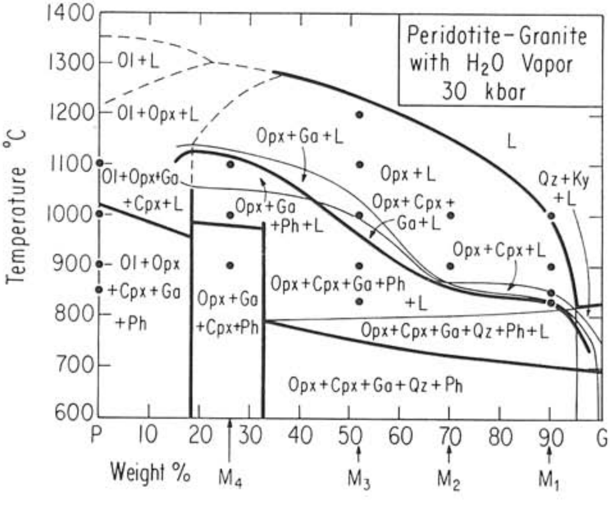

Fig. 4. Phase fields with a small amount of vapor in system peridotite-granite-H_2O. Complex subliquidus and subsolidus phase assemblages near granite are omitted. Note the subsolidus field for phlogopite-garnet-websterite separating fields with olivine and quartz (Sekine—Wyllie, 1982c).

mixing system would change along the line from L towards P. The liquid comsition precipitates phlogopite-garnet-pyroxenite, with evolution of aqueous vapor, until the last liquid is used up at the solidus (Fig. 4). Throughout this process the liquid composition remains rich in SiO_2 (Fig. 5). The effect of adding peridotite to the siliceous magma is to cause precipitation of cafemic minerals, with the Na_2O and K_2O from the liquid being transferred to jadeite component in clinopyroxene and to phlogopite, respectively. The final product is a body of phlogopite-garnet-websterite, with mineral compositions differing from those in the host peridotite, especially with respect to the clinopyroxene.

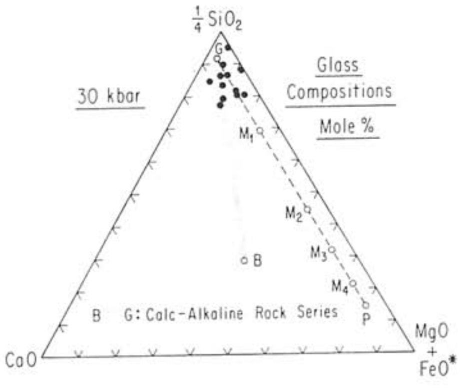

Fig. 5. The system peridotite-granite-H_2O: compositions of glasses projected into diagram for comparison with the starting mixtures (line PG) and the average chemical variation of the calc-alkaline igneous series (BG).

The mixing products in the system granite-peridotite-H_2O are directly analogous to those in the model system $KAlSiO_4$—Mg_2SiO_4—SiO_2—H_2O (Fig. 1). The join Ph—En in the model system serves the same function as a mineral-precipitation barrier between the low-temperature, hydrous siliceous liquid and the subsolidus peridotite, as does the subsolidus interval for phlogopite-garnet-websterite in the rock system (Fig. 4).

Reaction products between hydrous granite melt and peridotite

Sekine—Wyllie (1983) sealed crushed samples with water into gold capsules. In one arrangement, material was added to the capsule in the sequence water, granite, and peridotite, from bottom to top of the capsules, which were set vertically during a run. The peridotite was subsolidus in runs between 850 °C and 1,000 °C and just above the solidus at 1,500 °C. The granite was completely molten in all runs. New minerals developed along the boundary between the granite liquid and the peridotite.

Fig. 6A is a sketch of the polished surface through a typical charge. The garnet peridotite consists of tightly interlocking grains, and the granite is a body of clear glass. The reaction zone between the granite glass and peridotite contained large crystals up to 50 m diameter. In some runs, the larger minerals are isolated from the reaction zone, and completely enclosed by granite glass.

The peridotite cylinder sank into the granite liquid, as illustrated in Fig. 6A by the presence of narrow borders of granite glass occurring between peridotite and capsule walls. The reaction zone between the two materials was as well developed along the liquid.

Run # 10 is significantly different physically from all other runs, as illustrated in Fig. 6B. The granite body has lost its regular outline. It appears to have been quenched in the process of rising through the peridotite, which now surrounds the glass completely, at least in this section. Fingers of granite glass extend into the overlying peridotite from the main granite mass.

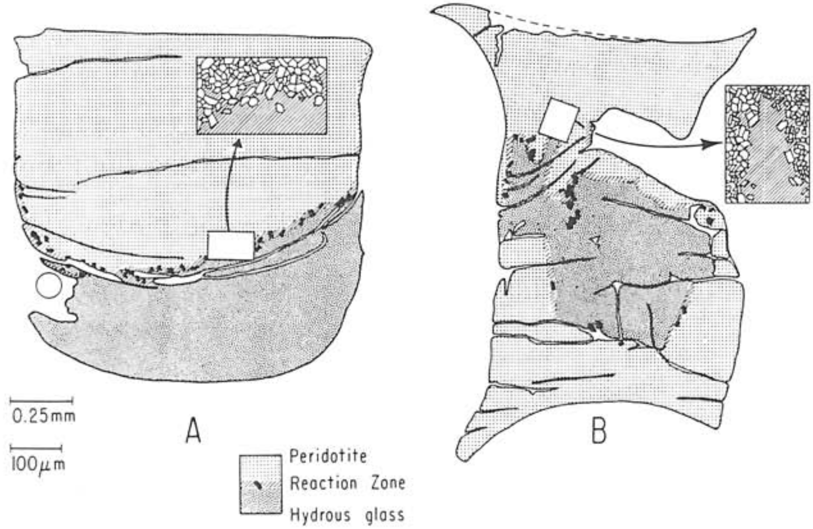

Fig. 6. Sketches of polished sections of quenched run products for crystalline peridotite above granite melt. A. Run #30, at 1,000 °C for 45 hours. Minerals in the reaction zone are orthopyroxene, jadeitic clinopyroxene, and quartz. B. Run #10, at 850 °C for 120 hours. Minerals in the reaction zone are orthopyroxene, jadeitic clinopyroxene, and suspected quartz. Phlogopite is distributed through the peridotite mass.

The results are influenced by processes occurring in stages. The first stage involves the melting of granite and the reaction of peridotite with aqueous vapor. We described the product as metasomatized peridotite. During and after withdrawal of the aqueous vapor into the granite liquid, reaction between the liquid and peridotite causes precipitation of new minerals in a hybrid reaction zone. The hybridization zone remains narrow through 120 hours, the longest run completed.

The mineral assemblages produced by hybridization contain the ubiquitous products orthopyroxene and jadeitic clinopyroxene. The occurrence of additional minerals garnet, quartz, and phlogopite does not fit any obvious sequence with respect to temperature.

Implications for magma genesis

Fig. 7 is an idealized cross-section through a subduction zone, with slab dipping at 45°, which illustrates the relative positions of source materials, dehydration and melting reactions, and identifies locations for the metasomatism and hybridization discussed below. The thermal structure corresponds to a subducted crust cooled (but not cooled to extreme conditions) by endothermic dehydration reactions (Anderson et al., 1978; 1980), and a mantle wedge warmed by induced convection (Toksoz — Hsui, 1978). With the present uncertainty about thermal structures, we have much latitude for interpretation of petrological processes. Reactions in subduction zones are commonly discussed in qualitative fashion without reference to phase boundaries with specific depth-temperature values. Possible reactions are more effectively evaluated when plotted in their correct relative positions for particular thermal structures. The locations of dehydration fronts, solidus boundaries, areas of potential melting, and the variations of their positions for different thermal structures were reviewed by Wyllie (1979; 1982).

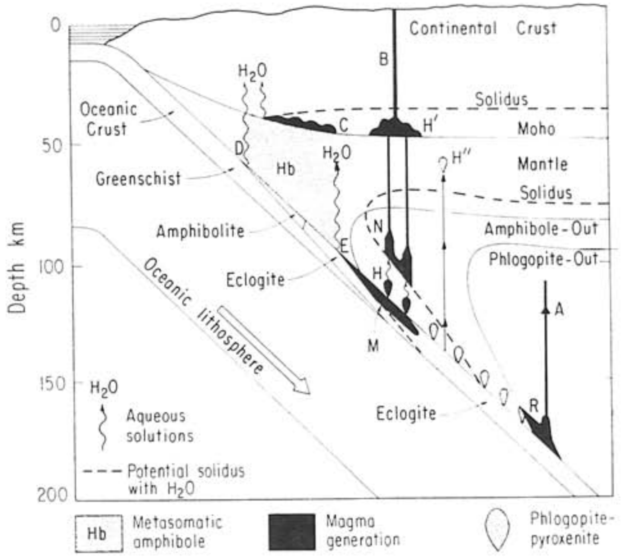

Fig. 7. Idealized petrological cross-section through subducted oceanic lithosphere, for a specific thermal structure with isotherms dominated by cooling of oceanic crust by endothermic dehydration reactions, and warming of mantle wedge by induced convection. See Wyllie (1979; 1981; 1982) for the locations of dehydration and melting fronts for varied thermal structures.

The aqueous solutions released in dehydration reaction may be transported across the solidus line for amphibolite or quartz eclogite in the subducted oceanic crust, causing partial melting represented in Fig. 7 at the location M. H_2O-rich, but H_2O-undersaturated, magma rises from the region M into the overlying peridotite. Will the liquid continue to rise, or will it hybridize and solidify?

From evaluation of the model systems, and from equilibrium mixing studies and reaction zone studies in the system peridotite-granite-H_2O, we can conclude that during hybridization between relatively cool hydrous siliceous magma and the hotter overlying mantle peridotite: 1) the magma experiences only minor changes in composition at temperatures below the solidus for peridotite-H_2O; 2) the dominant hybrid product is an olivine-free pyroxenite, with orthopyroxene and jadeitic clinopyroxene; 3) accessory minerals garnet, phlogopite, and quartz may occur; 4) aqueous vapor must be exsolved from the magma during hybridization; 5) the magma, if separated from its source and transported deeper by mantle convection, would solidify to pyroxenite; 6) the magma may rise through a succession of conduits, leaving layers of hybrid pyroxenites on the walls, which may be conveyed to deeper levels as discrete bodies; and 7) discrete bodies of phlogopite-rich rocks may be formed. The heterogeneous layer thus produced above the subducted oceanic crust provides: 1) aqueous fluids expelled during hybridization and solidification, which rise to generate in overlying mantle (given suitable thermal structure) H_2O-undersaturated basic magma, which is the parent of the calc-alkalic rock series erupted at the volcanic front; 2) masses of phlogopite-pyroxenites which melt when they cross a deeper, high-temperature solidus, yielding the parents of alkalic magmas erupted behind the volcanic front; and 3) blocks of phlogopite-pyroxenites which may rise diapirically for long-term residence in continental lithosphere, H", and later contribute to the potassium (and geochemically-related elements) involved in some of the continental magmatism, with geochemistry ascribed to mantle metasomatism.

If hybridization occurs in subduction zones, a great variety of possible magmatic processes is introduced, involving rocks, magmas, and aqueous fluids. Nicholls — Ringwood (1973) proposed that hybrid olivine pyroxenite generated in the mantle wedge constituted a suitable source material for the calc-alkaline magma series, with suitable adjustments caused by crystal fractionation at shallower depths. We have demonstrated that the product of hybridization is an olivine-free pyroxenite, different chemically and mineralogically from other materials considered as source rocks for magmas in subduction zone environments. However, olivine would be involved for melting occurring at the boundary between peridotite and pyroxenite. The clinopyroxene is extremely enriched in jadeite compared with that in mantle peridotite, and probably richer in jadeite than the clinopyroxene in subducted oceanic crust (although uncertainties about the degree of metasomatism of oceanic crust temper this conclusion). In oceanic crust, the path of progressive fusion is controlled by clinopyroxene and garnet, whereas in a hybrid pyroxenite the liquid path would be controlled by orthopyroxene and clinopyroxene. In order to translate the results of isotope and trace element geochemistry of subduction zone igneous rocks, we need to know more not only about the compositions of melts derived by partial fusion of mantle and subducted oceanic crust, but also more about the compositions of various hybrid rocks that may be produced in the mantle wedge.

Acknowledgements: This research was supported by the Earth Sciences Section of the National Science Foundation, Grants EAR 82-06178 and EAR 83-41623.

REFERENCES

ANDERSON, R. N. — DELONG, S. E. — SCHWARTZ, W. M., 1978: Thermal model for subduction with dehydration in the downgoing slab. J. Geol. (Chicago), 86, pp. 731—739.

ANDERSON, R. N. — DELONG, S. E. — SCHWARTZ, W. M., 1980: Dehydration, asthenospheric convection and seismicity in subduction zones. J. Geol. (Chicago), 88, pp. 445—451.

NICHOLLS, I. A. — RINGWOOD, A. E., 1973: Effect of water on olivine stability in tholeiites and production of silica-saturated magmas in the island arc environment. J. Geol. (Chicago), 81, pp. 285—300.

SEKINE, T. — WYLLIE, P. J., 1982a: Phase relationships in the system $KAlSiO_4$—Mg_2SiO_4—SiO_2—H_2O as a model for hybridization between hydrous siliceous melts and peridotite. Contr. Mineral. Petrology (Berlin — New York), 79, pp. 368—374.

SEKINE, T. — WYLLIE, P. J., 1982b: Synthetic systems for modeling hybridization between hydrous siliceous magmas and peridotite in subduction zones. J. Geol. (Chicago), 90, pp. 734—741.

SEKINE, T. — WYLLIE, P. J., 1982c: The system granite-peridotite-H_2O at 30 kbar, with applications to hybridization in subduction zone magmatism. Contr. Mineral. Petrology (Berlin — New York), 81, pp. 190—202.

SEKINE, T. — WYLLIE, P. J., 1983: Experimental simulation of mantle hybridization in subduction zones. J. Geol. (Chicago), 91, pp. 511—528.

SEKINE, T. — WYLLI,E, P. J., 1982c: The systems granite-peridotite-H_2O at 30 kbar, for quartz eclogite composition in CaO—MgO—Al_2O_3—SiO_2—H_2O with implications for subduction zone magmas. Amer. Mineralogist (Washington), 66, pp. 938—950.

STERN, C. R. — WYLLIE, P. J., 1978: Phase compositions through crystallization intervals in basalt-andesite-H_2O at 30 kbar, with implications for subduction zone magmas. Amer. Mineralogist (Washington), 63, pp. 641—663.

TOKSOZ, M. N. — HSUI, A. T., 1978: Numerical studies of back-arc convection and the formation of marginal basins. Tectonophysics (Amsterdam), 50, pp. 177—196.

WYLLIE, P. J., 1979: Magmas and volatile components. Amer. Mineralogist (Washington), 64, pp. 469—500.

WYLLIE, P. J., 1981: Plate tectonics and magma genesis. Geol. Rdsch. (Stuttgart), 70, pp. 128—153.

WYLLIE, P. J., 1982: Subduction products according to experimental prediction. Geol. Soc. Amer. Bull. (New York), 93, pp. 468—476.

WYLLIE, P. J. — DONALDSON, C. H. — IRVING, A. J. — KESSON, S. E. — MERRIL, R. B. — PRESNALL, D. C. — STOLPER, E. M. — USSELMAN, T. M. — WALKER, D., 1981: Experimental petrology of basalts and their source rocks. Chapter 3. In "Basaltic Volcanism on the Terrestrial Planets." Basaltic Volcanism Study Project. Pergamon, New York, pp. 493—630, 1286 pp.

YODER, Jr., H. S., 1976: Generation of basaltic magma. Nat. Acad. Sci., Washington, D.C.

Manuscript received November 17, 1984