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Presentation of the Roebling Medal of the Mineralogical Society of America for 1999 to Ikuo Kushiro

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Characterization of rock-forming processes requires laboratory experiments to determine physicochemical properties of these materials or their analog model compounds at high temperatures and high pressures. Those data are, however, only useful to earth scientists when integrated with observational and theoretical information. Ikuo Kushiro approaches experiments with this integrated view as his guiding light. He does experimental petrology, geochemistry, and geophysics with the clear understanding that the experimental data provide only a piece of a more complex puzzle. All too often we ask what experiments can be carried out and how to interpret the experimental data. Then we look for an application to rock-forming processes. Ikuo first asks the real question and then designs the experiment.

Ikuo Kushiro's career as an experimentalist began shortly after receiving his Ph. D. from the University of Tokyo in 1962. At that time he was appointed research associate at the university. Within months, however, we find him at the Geophysical Laboratory of the Carnegie Institution of Washington, where he spent the ensuing three years as a post-doctoral fellow working with Frank Schairer and Hat Yoder. This was a very active period where experimental studies of olivine + 2 pyroxenes + aluminosilicate phases led to the establishment of the principal phase relations governing basalt petrogenesis at high pressure and temperature.

Upon his return to the University of Tokyo in 1965, Ikuo began a collaboration with S. Akimoto. Together, they initiated a search for mineralogical storage of H_2O in the Earth's interior. In 1967, Kushiro, Syono, and Akimoto reported that phlogopite is such a mineral with pressure-temperature stability well into the upper mantle. In 1968, working with Tony Erlank, the H_2O-bearing mineral potassium-richterite was found to have a comparable stability field. Subsequent experimental work in laboratories around the world has reconfirmed these as two of the most important minerals with which H_2O can be recycled into the Earth's interior.

The experimental results on hydrous phases in the upper mantle led naturally to the question of how H_2O might affect melting phase relations of peridotite. In 1968, Kushiro, Syono, and Akimoto reported that the solidus temperatures of hydrous peridotite are 400–500 °C lower than in the absence of H_2O. This observation implied that temperatures near 1000 °C were sufficient to initiate melting of peridotite in the Earth's upper mantle. That observation was key to our understanding of magma genesis near convergent plate boundaries.

The profound effect of H_2O on the solidus temperature of peridotite implies that the bulk composition of the partial melt also must depend on the activity of H_2O. This effect was established when Kushiro, Yoder, and Nishikawa in 1968 reported that enstatite + H_2O melts incongruently to olivine + liquid, and when Kushiro in 1969 found that the olivine + clinopyroxene + orthopyroxene + liquid invariant point in the diopside-enstatite-olivine-H_2O system lies on the quartz-normative side of the diopside-enstatite join. Recall that in the absence of H_2O enstatite melts congruently at $P > 0.2$ GPa and the invariant point in the olivine + 2 pyroxene system is located on the olivine-normative side of the diopside-enstatite join. These results made it possible to generate quartz-normative magmas during partial melting of peridotite in island arcs upper mantle at comparatively low temperatures.

Ikuo Kushiro returned to the Geophysical Laboratory in 1967 and was appointed to the permanent staff in 1971. At that time he continued the experimental work on the role of H_2O during partial melting in the upper mantle. During this period, Ikuo also began to examine the systematics of liquidus phase relations as a function of the type of oxide components added to simple silicate systems. This work led to a simple and elegant model that describes the relationships between silica activity and the electronic properties of the oxide components in silicate melts.

Ikuo never thought that experimental studies of phase relations provided all the answers needed to characterize rock-forming processes in the Earth. For example, in the years between 1975 and 1980 he devoted much of his energy to the experimental examination of the properties of magmatic liquids, including rheology and equation-of-state of molten silicates. His adaptation of the falling-sphere technique to the solid-media, high-pressure apparatus in 1976 provided the means for simultaneous determination of melt density, compressibility, and viscosity at magmatic temperatures to pressures of about 3 GPa. At that time, we had no experimental data on these properties at pressures above ~0.2 GPa, and even those data were limited to a singular hydrous rhyolite melt composition. Ikuo, working with colleagues at the Geophysical Laboratory, reported melt viscosity and density of basalt and andesite both anhydrous and with dissolved H_2O (in andesite). One of the most surprising observations reported at the time was that anhydrous magmatic liquids become significantly less viscous with increasing pressure. Ikuo also noted that this pressure effect diminished when H_2O was dissolved in the melt and the pressure effect on melt viscosity was more pronounced for felsic than for mafic magmatic liquids. He also studied the rheological behavior of simple systems with the aim to develop a better understanding how individual components might influence melt viscosity. Interestingly, Ikuo's data on basalt compressibility were used as a basis for the proposals by Stolper, Walker, Hager, and Hays in 1981 of density inversions involving crystals and melts in the deep upper mantle

Ikuo Kushiro was appointed full professor at the University of Tokyo in 1974. He held a concurrent position as a staff member at the Geophysical Laboratory until 1981 when he needed to choose between the two locations and returned to Tokyo on a permanent basis. In Tokyo, Ikuo immediately focused on experimental examination of igneous processes in island arcs, but this period also coincided with rich new meteorite finds in Antarctica. These finds naturally drew Ikuo's attention to the extraterrestrial environment. An understanding of the rock-forming processes in this environment required unconventional experimental thinking. This obviously appealed to Ikuo's fertile mind, and he quickly designed an experimental apparatus for high-temperature, high-vacuum experiments. The result was a series of experimental studies that focused on the petrogenesis of Ca,Al-rich inclusions and chondrules in chondritic meteorites. These experimental studies provided liquid-crystal-gas invariant points for refractory phases such as hibonite, spinel, and forsterite. From these data, constraints were provided for the condensation sequences in the early solar nebula.

The last decade saw Ikuo Kushiro drawing on his vast research experience, teaching students, and producing graduates who quickly established themselves in their chosen subdisciplines. The administration at the University of Tokyo obviously also noticed Ikuo's success and appointed him dean of the faculty of science in 1991 and vice-president of the University of Tokyo in 1993 until his retirement in 1994. Most people would probably have found these jobs to be full-time endeavors, but not Ikuo. He continued an active research career during this period filled with administrative changes at the university with an average of about four published papers per year. Among these were several papers on partial melting of mantle peridotite utilizing a novel diamond sponge technique to extract small fractions of partial melt from the crystalline residue. This technique was an important innovation because until that time experimental studies of low degree of partial melting had remained a major problem as the melt fractions required for quantitative electron microprobe analysis effectively limited experiments to conditions under which analysis of the melt could be carried out. The diamond sponge technique removed this obstacle and in the following years became the method of choice for experiments of this type. Although we had a qualitative sense that the melt formed in the ≤5% degree melting range probably would be silica- and alkali-enriched; these assumptions could, and were, tested.

Following his retirement from the University of Tokyo in 1994, Ikuo moved to the Institute for the Study of the Earth's Interior (ISEI) of the Okayama University. During his five-year tenure there while simultaneously pursuing his own research interests, he quickly became the institute director and proceeded to develop ISEI, which is now one of the pre-eminent facilities in the world.

It is difficult to identify anyone more worthy of the Roebling Medal than this year's recipient. We, therefore, have the great pleasure to introduce to you Ikuo Kushiro as the medalist for 1999.