



Inside the Experimental Lab: Where fire and pressure force fearful rocks to confess

Tantalum and Niobium: Science, statistics and supply considerations

Cultivating an Eon Rose: A new hybrid variety seeks multidisciplinary input to flourish and flower

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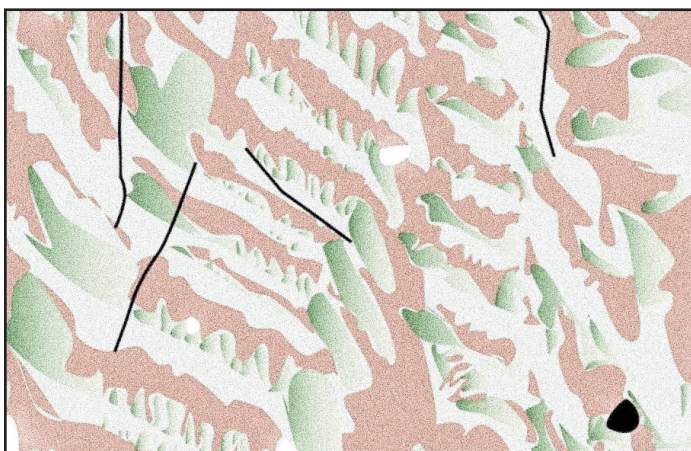
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**Cover Image:** Artisanal mining is an important factor in the tantalum industry, and is especially widespread in Africa. The photo depicts ground-slucing of ore at the Nyabitare pegmatite in Rwanda, where weathered ore is largely concentrated by such methods (photo Richard Burt).

# SERIES



## Igneous Rock Associations 22. Experimental Petrology: Methods, Examples, and Applications

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### SUMMARY

Experiments are an important source of basic information in petrology, from thermodynamic data used to develop predictive models to physical property data used to understand magma ascent and eruption. Since we all use experimental data in our work as geoscientists, it is important that we have a basic understanding of the methods used to prepare and perform experiments on rocks and minerals and their synthetic analogues. In this review I examine how the observational science of geology changed in the late 1800's with the development of the interdisciplinary science of physical chemistry. The second part of the paper discusses what factors need to be considered in designing an experimental study; it focuses particularly on the problems of reaching equilibrium on the short timescales available in the laboratory. In the final section, I give four examples of geological problems that have been solved using experimental methods and make some suggestions about the directions that future experimental campaigns might take.

### RÉSUMÉ

L'expérimentation est une source importante d'information de base en pétrologie, qu'il s'agisse de données thermodynamiques pour développer des modèles prédictifs, ou des propriétés physiques utilisés pour comprendre la montée et l'éruption d'un magma. Puisque nous utilisons tous des données expérimentales dans notre travail de géoscientifique, il est important que nous ayons une compréhension minimale des méthodes utilisées pour préparer et réaliser des expériences sur les roches, les minéraux et leurs analogues de synthèse. Dans la présente étude, je me suis penché sur les changements survenus en science d'observation qu'est la géologie, à la fin des années 1800, avec le développement de la science interdisciplinaire de la chimie physique. La deuxième partie de l'article traite des facteurs à prendre en compte dans la conception d'une étude expérimentale; elle porte en particulier sur les problèmes d'atteinte d'un équilibre sur les temps courts du laboratoire. Dans la dernière section, je donne quatre exemples de problèmes géologiques qui ont été résolus à l'aide de méthodes expérimentales, et je fais des suggestions sur des orientations qui pourraient être adoptées lors de campagnes expérimentales à venir.

*Traduit par le Traducteur*

### INTRODUCTION

*"The test of all knowledge is experiment. Experiment is the sole judge of scientific "truth". But what is the source of knowledge? Where do the laws that are to be tested come from? Experiment, itself, helps to produce these laws in the sense that it gives us hints"* (Feynman et al. 1963). Strong words indeed from one of the great theoreticians of science. In the Earth sciences, we experiment when we subject a geological material to a simulation of the conditions in or on the Earth. But what purpose do experiments serve? After all, they cannot simulate the passage of geological time, emplacement of a large magma body or even an entire lava flow.

Medawar (1968) described two types of experiment that are relevant to Earth scientists:

*Baconian experiments*, which he describes as contrived experiences designed to determine what will happen if we do x to y, and *Critical experiments*, designed to test a hypothesis.

In petrology, our experiments are often of the first type and most are done to increase the stockpile of knowledge, without which we would be hard-pressed to interpret our field data. Such experiments often provide the building blocks for models that allow us to calculate the pressure, the temperature, or some other property of real rocks. For example, the ther-

mododynamic data derived from experiments has been of critical importance to the development of internally consistent thermodynamic models such as the widely used MELTS models first developed by Ghiorso and Sack (1995). In a similar vein, experiments to measure magma properties, such as viscosity, have provided us with a robust model that can be used to calculate the viscosity of natural melts (Giordano et al. 2008) to aid in modelling and understanding of volcanic processes. Critical experiments are also a major part of experimental petrology. Classic examples are the experimental studies done in the late 1960's and throughout the 1970's to test Ringwood's (1966) hypothesis that basaltic magma is generated by melting of peridotitic mantle.

Experimentation on rocks has a long history. Sir James Hall, sometimes referred to as the Father of Experimental Petrology, was melting rocks in gun barrels in the early 1800's (Hall 1805). However, the utility and power of experimental petrology has not always been fully appreciated. In 1861, Darwin commented "*About thirty years ago there was much talk that geologists ought only to observe...*" (in a letter to H. Fawcett, 18 September 1861; Burkhardt and Secord 1985). It took another 60 years for experimental studies to be widely accepted. F.D. Adams noted in his Presidential Address to the Geological Society of America that "*Observation is the great basis and foundation stone of the science of geology; but as a companion and helper on this delightful, but sometimes toilsome, path – and more especially in the later years – observation has had the support of experiments, which while of distinctly subordinate and collateral value as compared with observation, has nevertheless rendered many important services in the development of geological knowledge*" (Adams 1918).

## EXPERIMENTAL PETROLOGY AS AN OFFSHOOT OF PHYSICAL CHEMISTRY

In the late 1800's physical chemistry became one of the first interdisciplinary fields in science. Between 1875 and 1878, J.W. Gibbs published his papers on equilibria in heterogeneous systems including a derivation of the phase rule (Gibbs 1874–1878). Ostwald, Van't Hoff and Arrhenius developed critical concepts in physical chemistry that are still applied in Earth sciences today. The idea that the phase rule could be used to predict the behaviour of chemical systems undergoing melting or crystallization was developed by Roozeboom (1901) who established the phase relations of a large number of systems both theoretical and based on metallurgical experiments (Eugster 1971; Cahn 2000). The stage was set for the application of thermodynamics to geological systems.

Harker (1909) recognized that "*recent developments of physical chemistry indicate at least the general lines upon which a more systematic treatment may be attempted*" and "*we may hope that the petrologist will soon be provided with data enabling him to introduce into the discussion of rock genesis the quantitative element, which hitherto has been almost wholly lacking*". At that time, there was very little information available on the melting and freezing points of igneous rocks, let alone information on the nature of solid solutions and phase relations of minerals. At best, there were experiments on metallurgical slags (Vogt 1903) and Roozeboom's (1901) theoretical work on solid solutions. An understanding of the

melting and crystallization temperatures and the nature of solid solution in minerals would only come after the studies of Day et al. (1905) and Bowen (1913).

Before there could be any systematic study of the temperature dependence of phase relations in geological systems the problem of temperature measurement had to be solved. Early attempts at measuring high temperatures relied on the Wedgewood pyrometer, which related temperature to the change in shape of clay cylinders in pottery kilns (see Young 1998, p. 17), but these were not very precise. The discovery of the Seebeck effect led to the development of thermocouples, in particular, the platinum–rhodium thermocouple (Le Châtelier 1886) but the lack of a reliable calibration hampered further development. The systematic work of Day and Allen (1904) and Day and Sosman (1911, 1912) to calibrate platinum–rhodium thermocouples against nitrogen gas thermometers allowed precise temperature measurement to 1755°C. This, and the early phase equilibria experiments of Shepherd et al. (1909) in the CaO–MgO–Al<sub>2</sub>O<sub>3</sub>–SiO<sub>2</sub> system, prepared the way for subsequent systematic studies, mostly led by Bowen (see Young 1998 for a detailed account).

Up to the 1960's, most of the work on analogue and natural melts relevant to basaltic systems focused on phase relations during crystallization at atmospheric pressure. This culminated in the development of the basalt tetrahedron and recognition of the thermal divide that separates the alkaline basalt series from the tholeiitic series (Yoder and Tilley 1962). This is not to say that research at high pressure had not been considered. Bridgman had been experimenting with a variety of apparatus, though his work was at relatively low temperature and focused mainly on the behaviour of simple compounds (Bridgman 1914, 1915, 1916, 1918). Goranson (1931, 1932) examined the high-pressure phase equilibria of granitic compositions and Hall and others developed apparatus capable of creating high pressure and temperature simultaneously in their pursuit of synthetic diamonds (Hall 1954, 1957, 1958, 1959, 1964; Hall et al. 1958; Hall and Kistler 1958), but it was not until the development of the piston-cylinder press (Boyd and England 1960) that high pressure and high temperature studies of geological systems became feasible. This new apparatus resulted in hundreds of studies in synthetic and natural systems.

In experiments on simple synthetic systems, such as those by Bowen and Andersen (1914) the phases were easily identified with the polarizing microscope or with x-ray diffraction techniques. In more complex natural systems, the small size of the experimental charges meant that the wet chemical techniques that were applied to real rocks were not feasible for routine chemical analysis of mineral phases in experimental materials. However, at about the same time that the piston-cylinder press became generally available, experimental petrologists were given a new tool – the electron microprobe. The ability to analyze samples at the micron scale for a wide range of elements drove experimentalists to work in natural systems using real rocks (Green 1976).

By 1974, the phase relations of peridotite were well enough defined to warrant inclusion in a classic petrology text (Carmichael et al. 1974). Igneous petrology was now a multi-

disciplinary field that combined field geology, geophysics, geochemistry and experimental studies. In particular, the results of mantle melting experiments have provided a firm basis for interpreting subtle variations in basalt composition and mineralogy (Basaltic Volcanism Study Project 1981). Most studies of igneous rocks now incorporated knowledge from experiments in the interpretation of field-based petrologic and geochemical data.

As more experimental data entered the literature, the descriptions of the methods used by the experimentalists became increasingly technical and jargon-filled and, thus, difficult for the uninitiated to follow. Edgar (1973) and Holloway and Wood (1988) provided essential guides to the techniques and equipment used in experimental petrology. Since then there have been numerous specialized volumes that outline the state of the art in experimental petrology, e.g. Luth (1993).

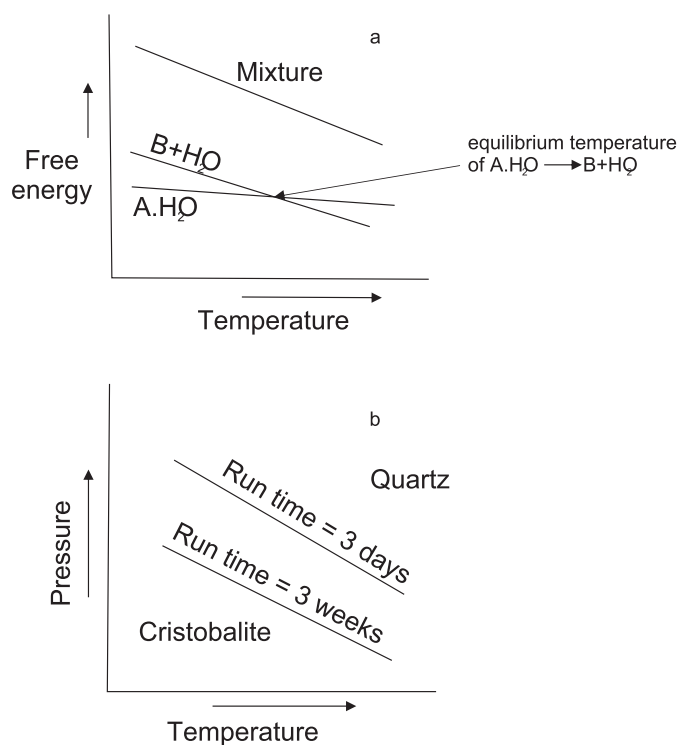
### DESIGNING A GOOD EXPERIMENT

Fortunately, it is not necessary to understand all of the technical details of an experimental study in order to make use of the results. Nevertheless, a basic understanding of experimental design is required for petrologists to understand the limitations of the results. In this review, I concentrate on the experimental design considerations and the issues that have to be faced in interpreting the results, with only a brief review of the equipment. The interested reader can find detailed descriptions of the construction and operation of various types of apparatus in Edgar (1973), Holloway and Wood (1988) and Luth (1993). I focus on experiments applicable to mafic igneous systems. This is not to say that experiments have not been done on intermediate and felsic igneous rocks or on metamorphic rocks, it simply reflects my personal interests and experience.

Experiments are both time consuming and expensive, so it is essential to ensure that they are well designed so as to minimize uncertainties in pressure and temperature and unnecessary complexity in the composition of the materials being studied. Modern experimental studies are typically designed to test a hypothesis or to define the rate of a geological process. Regardless of the aim, there are nine major issues that need to be considered before beginning an experimental campaign.

### The Experimental Charge

Experiments are designed to reproduce conditions within the Earth at the laboratory scale. We can generate the physical conditions of pressure, temperature, etc. relatively easily, but it is of course not practical to perform our experiments over geological timescales. This means that the material (i.e. the charge) in our experiment should be reactive enough to reach chemical equilibrium in a reasonable time frame, ideally hours to days. One way to obtain such a reactive material is to ensure that the charge is very finely powdered before loading into the experiment. Figure 1a shows an example from Fyfe (1960). In this system there are two complex silicate phases  $A.H_2O$  and  $B$  whose stability curves are shown. The ideal starting material for experiments to examine the stability of these phases will have a higher free energy than either of the phases, i.e. it will be less stable at the pressure and temperature conditions of



**Figure 1.** a) Ideal temperature – free energy relationship for a reactive starting mixture that will be used to examine the position of the equilibrium temperature of  $A.H_2O \rightarrow B + H_2O$ . The reaction curves intersect at the equilibrium temperature of  $A.H_2O \rightarrow B + H_2O$ . (Redrawn from Fyfe 1960). b) Results of cristobalite synthesis experiments as a function of run duration. Top boundary curve shows the quartz–cristobalite reaction curve for experiments run for three days. Bottom curve shows the quartz–cristobalite reaction curve for experiments run for three weeks. Without a method to test for equilibrium it is impossible to tell which curve is correct. It is possible that experiments run for months might give a different reaction curve. (Redrawn from Fyfe 1960)

the experiment. Importantly, however, the phase that forms first depends not on the equilibrium temperature, but rather on the interplay between nucleation and grain growth.

Our experiments aim to help us understand igneous rocks, but using a natural sample may not be the best option. In some cases, it is necessary to simplify the composition of the system, perhaps by leaving out trace elements, water, or another component to make the results of the experiment easier to interpret. If we choose not to use a natural sample as our starting material, then we need to prepare a synthetic composition. There are a number of options for a synthetic starting material (Edgar 1973):

1. Co-precipitated gels
2. Oxide mixtures
3. Pure minerals mixed in the desired amounts
4. A synthesized glass

Which one do we use? Fyfe (1960) reviewed this issue as it pertains to subsolidus reactions, in particular showing that experiments with highly reactive, amorphous gels can produce metastable assemblages that can persist for many months in an experiment. Figure 1b shows Fyfe's example of the shift in the position of the quartz–cristobalite phase boundary depending

on the duration of the experiments. Which, if either, of these phase boundaries is closest to the real one? If one's goal is to determine the equilibrium phase relations, then clearly avoiding such metastability is crucial and a method of assessing the approach to equilibrium is essential. Of the choices above, most experiments in igneous systems have chosen glass or a partially to completely crystallized glass prepared from oxide/hydroxide/carbonate mixtures. For example, Bowen and Anderson (1914) did their experiments in the MgO–SiO<sub>2</sub> system on glasses prepared from quartz and decarbonated MgCO<sub>3</sub>. Their procedure was as follows:

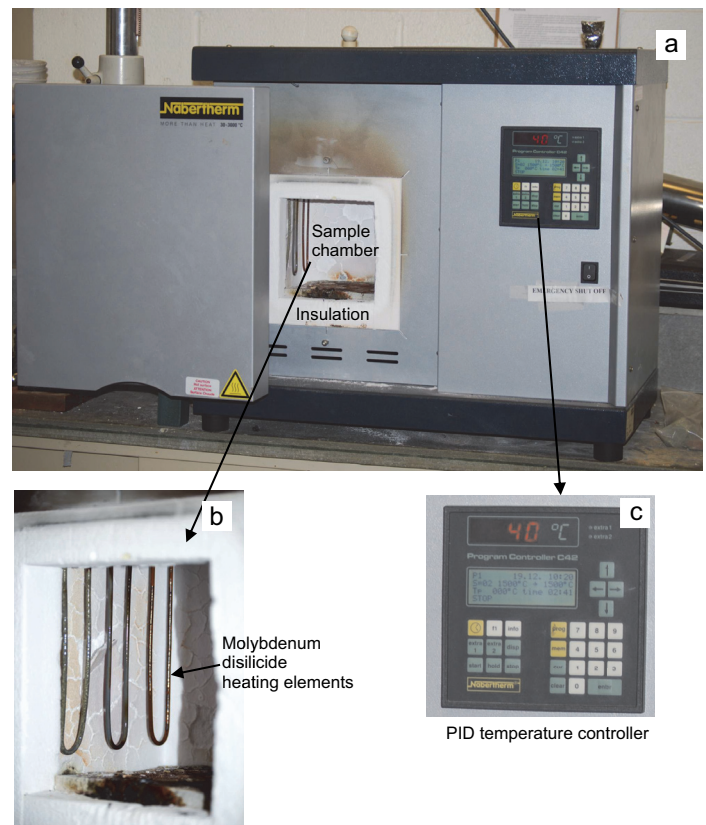
1. Prepare mixtures of the desired composition by weighing the oxides/carbonates, grind in an agate mortar to mix, and fuse to produce a melt, holding at temperature for one hour before rapid cooling to produce a glass.
2. Crush the resulting glass and repeat the fusion.
3. Analyze the glass to ensure that it has the desired composition.
4. Hold the glass at a temperature below the melting temperature to crystallize. For silica-poor compositions, crystallization takes a few minutes, but for silica-rich compositions, which can remain free of crystals at temperatures significantly below their liquidus, crystallization can take several days.
5. Grind the crystallized material to a fine powder and store in a desiccator.

This procedure is by far the most common method used to prepare materials for experiments. Even, so there can be problems in using the crystallized material. If it is ground too finely, the powdered crystals may have very large surface energies which can lead to metastability and thus to disequilibrium.

If a volatile, such as water or CO<sub>2</sub> is required as part of the sample charge, the experiment must be done in a sealed capsule at greater than atmospheric pressure. Water can be added in liquid form before sealing the sample capsule (see below), but if CO<sub>2</sub> is required it is usually added as a solid that will decompose at the experiment conditions to give the required amount of volatile.

### The Containment Problem

The sample must be contained in something and this container must: 1) be stable at the conditions of the experiment, and 2) not react with any of the materials being used – the furnace walls or elements, the thermocouple, or the material under investigation. The most common sample container is a platinum crucible or capsule but a variety of other materials, such as graphite, gold, silver, and molybdenum can be used. Platinum has a high melting temperature (1768°C), it is stable in both oxidizing and reducing conditions and it is unreactive to silicate melts, except those containing iron (Merrill and Wyllie 1973). In experiments that produce melt, iron in the melt will alloy with a Pt sample container so that over time the composition of the melt will change. This is a significant problem in older studies and a variety of methods have been developed to overcome it including pre-saturating the capsules with iron, using silver–palladium (AgPd), gold, graphite, or molybdenum



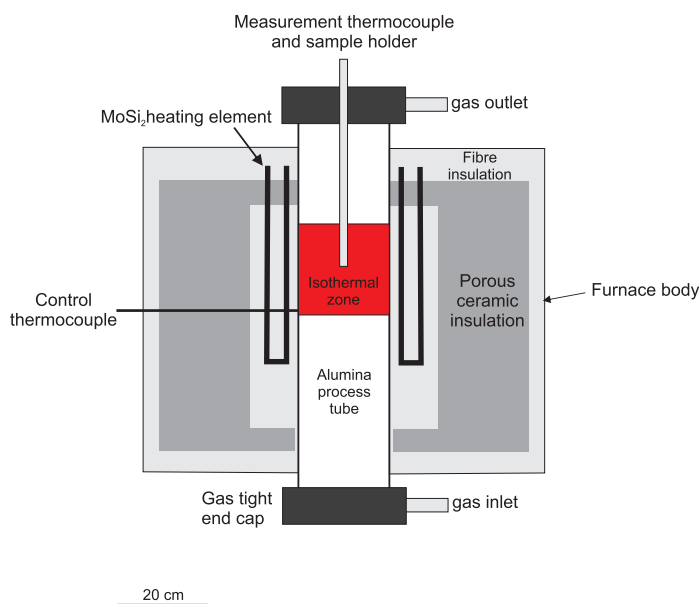
**Figure 2.** The Nabertherm 1650°C muffle furnace in the experimental petrology laboratory at University of New Brunswick. The sample chamber (a) has a working volume of around 3000 cm<sup>3</sup>. It is heated with U-shaped MoSi<sub>2</sub> elements (b) and the heating rate, heating duration and final temperature are controlled by the built in digital controller (c).

containers, or replacing iron in the starting material with cobalt which does not alloy with platinum.

If the sample contains volatiles, the encapsulating material must be able to be tightly sealed prior to the experiment and remain sealed during the experiment. Volatile-bearing experiments are typically done in welded platinum, AgPd, or gold capsules, depending on the temperature of the experiment.

### Generating High Temperatures

In the early days of experimental petrology, samples were heated in platinum-wound furnaces powered by storage batteries and controlled by large street-car-type banks of resistor coils (Yoder 1998). A wide variety of furnace designs have been developed since (e.g. Strong et al. 1942; Edgar 1973) and today, there are many commercial suppliers of furnaces that will easily reach temperatures in excess of 1600°C (Fig. 2, e.g. [www.nabertherm.com/produkte/labor/laboratory\\_english.pdf](http://www.nabertherm.com/produkte/labor/laboratory_english.pdf)). These furnaces come in a variety of shapes and sizes from the typical muffle furnace used for preparing large quantities of glass to tube furnaces in which samples can be heated under high vacuum or in a variety of gas mixtures (Fig. 3, see below). The heating elements are typically molybdenum disilicide (MoSi<sub>2</sub>) or less commonly silicon carbide. MoSi<sub>2</sub> elements are extremely stable up to 1800°C with long service lifetimes in a variety of furnace atmospheres.



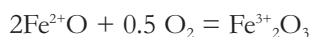
**Figure 3.** Schematic diagram of a one atmosphere tube furnace. The furnace is heated with MoSi<sub>2</sub> elements and temperature is controlled with a thermocouple attached to the outside of the process tube. The process tube is made of gas tight Al<sub>2</sub>O<sub>3</sub> and is sealed at both ends. Ports in the seals allow mixtures of gases to be pumped into the tube to control oxygen fugacity. The upper cap also has ports for a measurement thermometer and a sample holder. The isothermal zone of the furnace is approximately 20 cm long.

### Measuring and Controlling Temperature

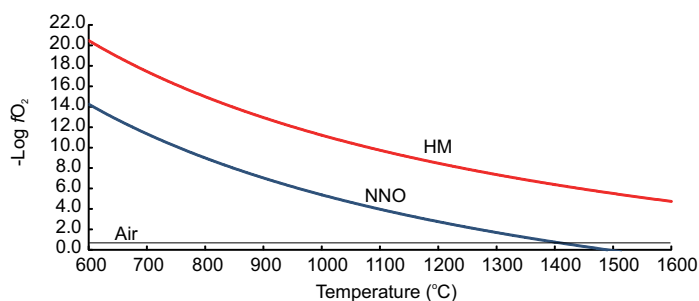
The most common temperature measurement instrument is the thermocouple. When two metals of different composition are joined at one end, any temperature difference between the joined and free ends of the wire will generate a small, but measurable electromotive force (*emf*) that is proportional to temperature. The choice of thermocouple depends on the temperature range of interest. In experimental petrology, type s and r platinum–rhodium thermocouples are the most common, but other types such as chrome–alumel and tungsten–rhenium are used as well. In most studies, the quoted precision on temperature is usually ± 5°C for experiments at 1 atmosphere and ± 10°C for high pressure experiments. The larger range for the high-pressure experiments is because usually no correction is made for the effect of pressure on the *emf* of the thermocouple.

### Oxygen Fugacity Control and Measurement

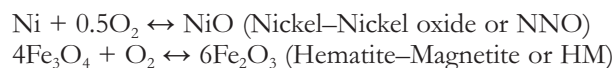
The availability of oxygen to the sample during an experiment controls the ratio of ferrous (Fe<sup>2+</sup>) to ferric (Fe<sup>3+</sup>) iron and other multivalence elements through redox reactions such as:



The equilibrium oxygen fugacity (*f*O<sub>2</sub>) of a reaction varies with temperature and there are numerous reference reactions that define a range of *f*O<sub>2</sub> values that are petrologically useful. In practice, we use these reactions (often referred to as buffers; Eugster 1957) to communicate information about the redox state of a rock or experiment. The relationship between *f*O<sub>2</sub> and temperature of two commonly used buffer reactions:



**Figure 4.** Temperature vs  $-\text{Log } f\text{O}_2$  plot showing the position of the relatively reducing Nickel–Nickel oxide (NNO) and oxidizing Hematite–Magnetite (HM) buffer curves. The oxygen fugacity of air is shown for reference.



is shown in Figure 4.

In one atmosphere experiments, *f*O<sub>2</sub> is controlled by redox reactions in gases, e.g. carbon monoxide and carbon dioxide:

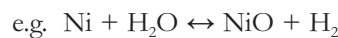


To fix *f*O<sub>2</sub> the partial pressure of the two gases is varied as shown below:

$$f\text{O}_2 = (\text{PCO}_2 / (\text{PCO} * k))^2$$

where *P* is the partial pressure of the gas phase and *k* is the equilibrium constant (Darken and Gurry 1945, 1946). The equilibrium constant can be determined from thermodynamic tables (kinetics.nist.gov/janaf/) and we use the partial pressure of the gases, rather than fugacity, since they can be considered to be ideal at the high temperature of most experiments.

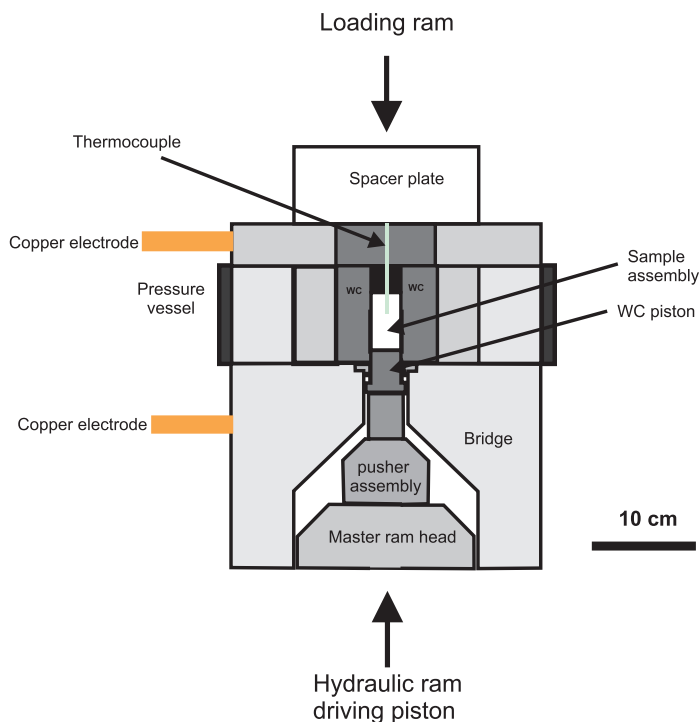
Solid buffers are commonly used in high pressure experiments where the use of gas mixtures is impractical. In this case, the encapsulated experiment charge is placed into a larger capsule that contains the buffer assemblage. Holloway and Wood (1988) note that when solid buffers are used, it is actually water that controls the oxygen fugacity:



For the solid buffer method to work, the sample capsule must be platinum or silver–palladium as they are permeable to hydrogen. Hydrogen formed in the buffer reaction can diffuse through the capsule walls to control *f*O<sub>2</sub> in the experiment. However, this means that the solid buffer method cannot be applied to anhydrous experiments. In such experiments, oxygen fugacity can be controlled by using a graphite capsule sealed inside a platinum capsule. In this approach, oxidation of the graphite produces carbon monoxide and the equilibrium between the two defines *f*O<sub>2</sub> (Médard et al. 2008).

### Generation of Pressure

Pressure can be applied to an experimental charge by a gas, liquid or deformable solid. Internally heated gas pressure vessels are used in some laboratories, e.g. Spickenbom et al. (2010);

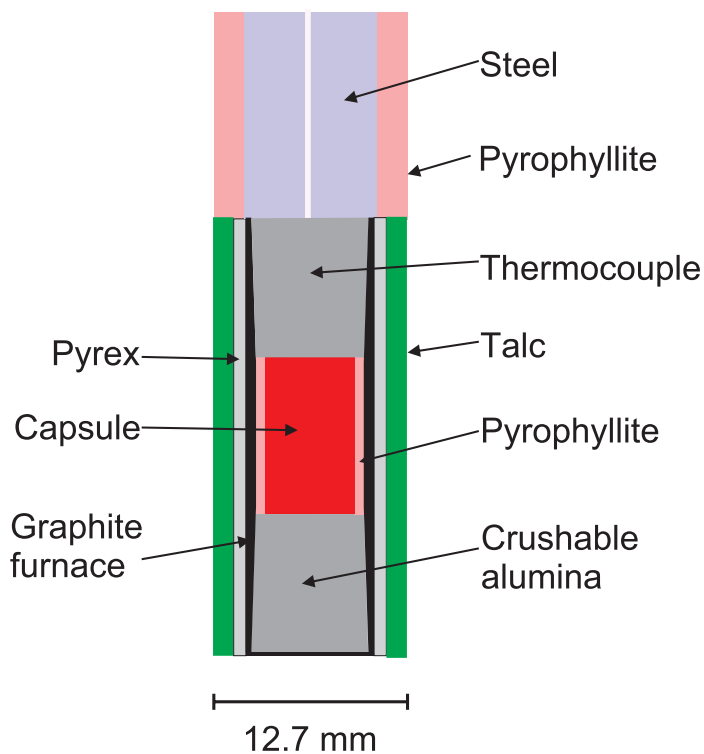


**Figure 5.** Components of the piston cylinder press showing the pressure vessel its supporting bridge which contains the mechanism for pushing the piston into the vessel. The pressure vessel is covered by a thermocouple plate topped with a spacer plate. This assembly is placed in a large press frame that holds two hydraulic rams. The upper ram compresses the entire assembly to add strength. The lower ram pushes the piston into the pressure vessel.

however, they are expensive, and require extensive shielding as failure of the pressure containment system will lead to a large explosion – the vessels are commonly referred to as ‘bombs’ for good reason! Pressure generation by a liquid, usually water, is limited to about 10 kilobars (Tuttle 1949; Wyllie and Tuttle 1960; Walter et al. 1962). At this pressure, the maximum temperature is limited to around 600°C by the hot rupture strength of the pressure vessel which means that hydrothermal pressure vessels are not particularly useful for studies of mafic igneous rocks.

The work horse of the experimental petrologist interested in mantle melting processes is the solid-media piston-cylinder apparatus (Fig. 5). This was designed by Boyd and England (1960) based on earlier designs by Coes (1955) and Hall (1958). The piston-cylinder can generate pressures from 0.5 to 6 GPa, though the most common range is 0.5 to 3 GPa. Samples are heated in a graphite resistance furnace that is contained within the solid pressure medium. Compared to one atmosphere experiments, the sample size is quite small, with a maximum capsule size of ~1 cm long and ~5 mm in diameter (Fig. 6). In early designs, the samples had to be much smaller because the graphite furnaces produced large thermal gradients. New furnace designs have decreased the gradient to around 10°C over the length of a 1 cm capsule (Schilling and Wunder 2004).

The piston-cylinder works by pressing a piston into a cylinder that contains a solid pressure medium, a heater and the sample (Fig. 6). The force applied by a large hydraulic ram, usually with a capacity of between 50 and 200 tonnes, is mul-



**Figure 6.** Schematic sketch of the solid pressure medium used in the piston cylinder press. The cell parts are produced in-house and a new cell is required for each experiment.

tiplied by the ratio of the ram area ( $A_1$ ) to the piston area ( $A_2$ ) as shown in Figure 7. Since the ram area is much larger than that of the piston, which has a diameter of either 0.5 or 0.75 inches, there is a significant multiplication factor for pressure ( $P$ ):

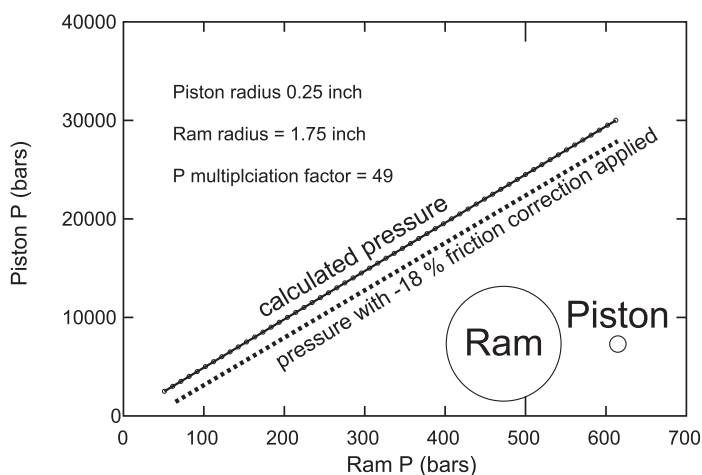
$$\begin{aligned} \text{Force} &= \text{Pressure} * \text{Area} \\ P_1 * A_1 &= P_2 * A_2 \\ P_2 &= P_1 * (A_1 / A_2) \end{aligned}$$

For example, at a pressure of 1000 pounds per square inch (69 bars), a hydraulic cylinder with a radius of 1.75 inches pushes a piston with a radius of 0.25 inches, the pressure multiplication factor is 49, so that the pressure applied to the sample in contact with the piston is 3381 bars or 0.338 GPa.

### Calibrating Pressure

Pressure generated by gas or water is hydrostatic and the pressure on the sample is simply the measured pressure within the pressure containment vessel. In a solid media apparatus like the piston-cylinder, the relative simplicity and greater safety come at a cost as the pressure experienced by the sample may be higher or lower than the nominal pressure depending on how the experiment is performed and the pressure medium used. Most of the deviation from the nominal pressure is due to the shear strength of the pressure medium which is usually made from either talc which has a significantly more shear strength than the alternative – NaCl. The deviation from nominal pressure, commonly referred to as being due to ‘friction’





**Figure 7.** A plot of ram pressure vs piston pressure for the 150 tonne piston cylinder press at the University of New Brunswick. The piston radius is 0.25 inches and the ram radius is 1.75 inches, giving a pressure multiplication factor of 49. The solid line shows the calculated pressure based on the load applied by the hydraulic ram. The dashed line shows the corrected pressure after calibration using the melting point of diopside.

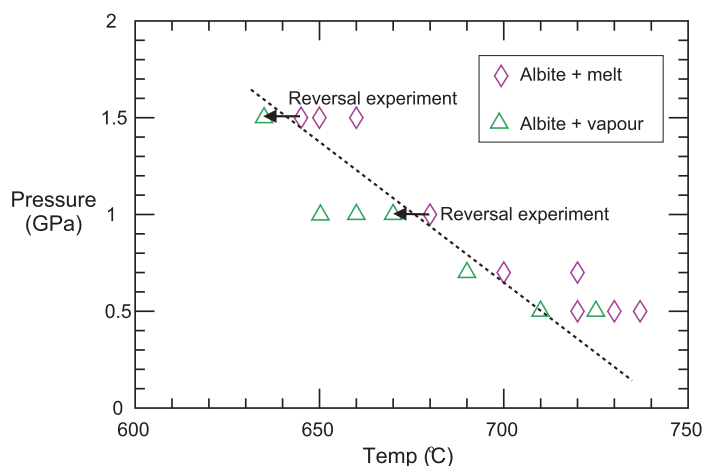
(see Johannes et al. 1971 for details), requires that the piston-cylinder be calibrated against a  $P$ - $T$  curve for a reaction that has been determined by some other means, either from thermodynamic data or from experiments in a gas pressure vessel.

Inside the talc or salt cell is a Pyrex glass liner that prevents reaction between the graphite furnace and pressure medium. The sample capsule is placed inside an alumina, pyrophyllite, or quartz glass sleeve to electrically insulate it from the furnace (Fig. 6). The entire pressure assembly is placed in a high-strength tungsten carbide (WC) cylinder that is surrounded by press-fit steel rings which apply a radial force that counteracts the extensional forces that occur during pressurization.

**Time: Equilibrium vs Kinetics**

One atmosphere experiments can be run indefinitely if there is a stable power source. High pressure experiments can also be for stable days or even weeks at temperatures below 1500 as long as there is a stable power supply and the thermocouple does not suffer contamination. Above 1500°C high pressure experiments are somewhat less stable but experiments may still have durations of 10's of hours with careful preparation.

In experimental studies of phase equilibria, it is essential that we know that the experimental charge reached thermodynamic equilibrium. But how do we prove that equilibrium has been attained, and what is the minimum time that is needed to attain equilibrium? One way to try to attain equilibrium quickly is to have a very finely ground starting material, so that the distance that elements have to diffuse to attain equilibrium is small. However, as noted earlier, there can be issues with metastability if the powders are too fine. Another way is to do two experiments, using the same material and conditions but at widely different durations. If the two experiments, one run for 1 hour and another for 100 hours, have the same homogeneous phases and phase compositions, then equilibrium is suggested. However, this approach does not prove that phases are in equilibrium. Fyfe (1960) noted that in experiments prepared



**Figure 8.** The  $P$ - $T$  relations in the albite-water system (data from (Bohlen et al. 1982)). The albite melting curve is shown by the dashed line. Reversal experiments were carried out to check for equilibrium at 1 and 1.5 GPa. Reversal experiments were first heated to the temperature above the melting curve and held there for ~7 hours after which they were cooled by 10°C. These reversals showed that the experiments at 670°C and 1 GPa and 635°C and 1.5 GPa had reached equilibrium. Note that at 0.5 GPa the position of the melting curve is not well defined and there appears to be one experiment at 735°C in which melt-free albite persists metastably.

from gels, cristobalite can exist metastably in the quartz stability field for months!

The only way to properly assess equilibrium is to perform reversal experiments. In their simplest form, these involve taking the composition of interest toward the boundary curve from two different directions. For example, in their experiments to determine the melting point of albite at 1 and 1.5 GPa in a  $H_2O$  fluid, Bohlen et al. (1982) did a series of experiments as shown in Figure 8. From these they estimated that the melting point of albite lies between 670 and 680°C at 1 GPa and between 635 and 645°C at 1.5 GPa. However, in both cases, the melting point is not well defined. The duration of the low temperature experiments might have been too short for melt to be generated. In other words, albite + vapour could have existed metastably. To determine if the melting temperature actually lies in the suggested range, Bohlen et al. (1982) did two additional experiments. They knew that at 1 and 1.5 GPa they had albite plus melt at 680 and 645°C respectively, so they started their experiment by heating their sample to the temperature at which melt was present and running it for the same time as in the first experiment after which they decreased the temperature by 10°C. If they were correct about the position of the melting curve, the decrease in temperature should have caused crystallization giving only albite + vapour. In both experiments, there was no melt present in the reversed experiment confirming the location of the melting curve.

In more complex systems, where there is one or more solid solution, reversal experiments require a more complex methodology. This is well illustrated by the work of Klemme and O'Neill (2000). In their experiments, rather than having a single starting material composition and changing pressure or temperature to change the direction of the approach to an equilibrium curve, they used two slightly different compositions. In detail, their approach to determining the position of

the garnet to spinel transition in peridotite involved having two starting materials with slightly different compositions of clinopyroxene and orthopyroxene. They showed that equilibrium was attained when the composition of the two pyroxenes in the two different starting materials was the same after the experiment.

### Maintaining Equilibrium During Cooling

Most reactions in geological materials are slow, so that the rate of cooling will not significantly affect their composition. There is a major exception to this; quench crystallization of silicate melt. This is a particular problem for mafic and ultramafic melts; in particular those that have even relatively low volatile contents. If cooling is not fast enough, these melts can show significant amounts of crystallization (Fig. 9). These crystals were not present at the experiment conditions, and their presence changes the composition of the equilibrium liquid.

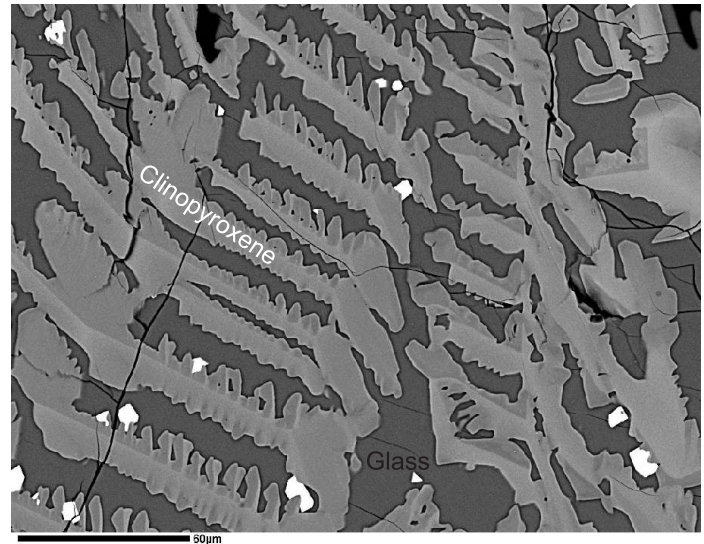
In experiments at one atmosphere, very rapid cooling can be achieved by dropping the sample into a container of coolant – water is the most common, though mercury baths and even liquid nitrogen have been used (Edgar 1973; Xu and Zhang 2002), this rapid cooling quenches the high temperature assemblage and transforms any melt present to a glass. For most compositions, this is an effective technique. However, even with cooling rates of a few hundreds of degrees per second, crystallization during quenching of the experiment can still be a problem. In their quest to produce a glass of peridotite composition, Dingwell et al. (2004) used a very rapid quenching technique, the splat quencher, in which the sample is dropped from the furnace and ‘splatted’ between two cold copper discs. This increases the surface area of the sample and so increases cooling rate.

At high pressure, quenching also relies on rapid cooling, although because of the large thermal mass of the apparatus, cooling rates are not as rapid in the piston-cylinder as they are in one atmosphere experiments. This leads to quench crystallization problems, particularly in water and CO<sub>2</sub>-bearing basaltic melt and in low percentage partial melts of peridotite. A variety of techniques have been developed to overcome the quench crystallization issues such as melt traps in glassy carbon or diamond or glassy carbon aggregates (Kushiro 1996; Van den Bleeken et al. 2011) or trapping melts as artificial melt inclusions in fractured minerals (Spandler et al. 2007).

## USING EXPERIMENTS TO ANSWER PETROLOGICAL QUESTIONS

### What Mineral Assemblages and Melt Compositions Form During Melting of the Mantle and Crystallization of Basalt?

To answer this question we need to produce phase diagrams from high pressure and high temperature melting experiments on peridotite and high temperature crystallization experiments on basalt and simple analogue compositions. Although every Earth science student learns to read phase diagrams as part of their undergraduate degree, many do not know how one goes



**Figure 9.** An example of quench crystallization of clinopyroxene in an alkaline basaltic melt. From Mumford (2006).

about ‘making’ a phase diagram. To illustrate how these diagrams are constructed, we examine two different types of experiment: near solidus melting experiments done at high pressure, and near liquidus crystallization experiments. It is important to realize that just as a geological map is a 2-D representation of the distribution of rocks and the contacts between different lithologies, a phase diagram represents the stability fields of minerals and the ‘contacts’ are where two or more phases are in equilibrium. As with maps, we never see the entirety of a stability field or a contact and we have to infer their position from a limited number of outcrops (experiments).

Phase equilibrium experiments have been a part of experimental petrology and materials science for more than a century, beginning with studies of metallurgical slags (Vogt 1903) and encompassing the classic studies of Bowen and coworkers (Bowen 1912; Bowen and Andersen 1914; Bowen and Tuttle 1950) to recent studies such as Mitchell and Grove (2016). Thermodynamic modelling software such as FACTSAGE for slag systems (Bale et al. 2002) and MELTS for natural silicate melts (Ghiorso and Sack 1995; Hirschmann et al. 1998; Asimow et al. 2001; Smith and Asimow 2005; Gualda et al. 2012; Gualda and Ghiorso 2014) is the result of almost a century of experiments on a wide variety of materials.

### Peridotite Melting Experiments

Experiments just above the solidus of peridotite at high pressure have been essential to our understanding of basalt genesis and the geochemical evolution of the mantle. The study of Jaques and Green (1980) was particularly instructive because it showed how temperature and pressure influence melt composition. For their experiments, Jaques and Green prepared a sintered oxide mixture of pyrolite, the model mantle composition proposed by Ringwood (1966). They modified the pyrolite composition so that it had 40% less olivine than the original. This removal of olivine served two purposes: it made minor

phases easier to detect, and it increased the amount of melt (glass) present in the experiments which decreased the effects of quench crystallization on the melt compositions. A first reaction to this approach might be to wonder how much effect removing the olivine has on the phase equilibria. The answer is almost none because even at the highest temperatures, their experiments were still saturated with olivine. Since the melts were olivine saturated, the removal of the excess olivine made no difference to the results. In fact, they did notice some small effects on the composition of the olivine crystals which were slightly more magnesian than those in equilibrium with the peridotite, but they considered this difference a small cost in order to obtain large pools of glass unaffected by quench crystallization for analysis.

The experiments were done at atmospheric pressure to 1.5 GPa over a temperature range of 1170 to 1550°C in a one-atmosphere furnace and a piston-cylinder press. The high pressure experiments used talc–pyrex cells with the sintered oxide mixtures encapsulated in platinum and temperature was measured with a type-S thermocouple. They calibrated the pressure in their cells against the quartz – coesite and albite = jadeite + quartz transitions and, because of the inherent shear strength of the talc pressure medium, applied a 10% correction to the nominal pressure determined for their piston-cylinder press. Since they were interested in anhydrous melting, they stored their starting materials and pressure cells at 110°C until they were ready to begin the experiment. They did not control the oxygen fugacity of the experiment, but they did note that based on earlier experiments with solid buffers they knew that the  $f_{O_2}$  was below the NNO buffer. The biggest issue that they had to overcome was the alloying of iron with the platinum capsules. They used very short run durations, 20 minutes at 1550°C and 5 hours at 1050°C, and for several  $P$ – $T$  conditions they did multiple experiments over a range of durations to examine the effects of progressive iron loss. To test for equilibrium they determined the partition coefficient of Fe and Mg between olivine and orthopyroxene in their experiments and compared it to the accepted value which had been determined in several earlier studies. This is not a particularly robust test of equilibrium and the problems of iron loss meant that it was impossible to do reversal experiments. Although Jaques and Green (1980) considered that their experiments had reached equilibrium, they were unable to prove it conclusively.

Once their experiments were complete, they identified the phases with SEM and determined mineral and melt compositions by electron microprobe analysis. They determined melt compositions in two ways: first by analyzing the pools of glass that were present in the experimental charge, and second by calculating the melt composition by mass balance using the initial pyrolite composition together with the composition and modal abundance of the crystalline phases in the experiment. The calculated melt compositions are more magnesian with higher FeO and lower SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and CaO than the analyzed glass which possibly reflects modification of the glass by quench overgrowths on the surrounding crystals during cooling.

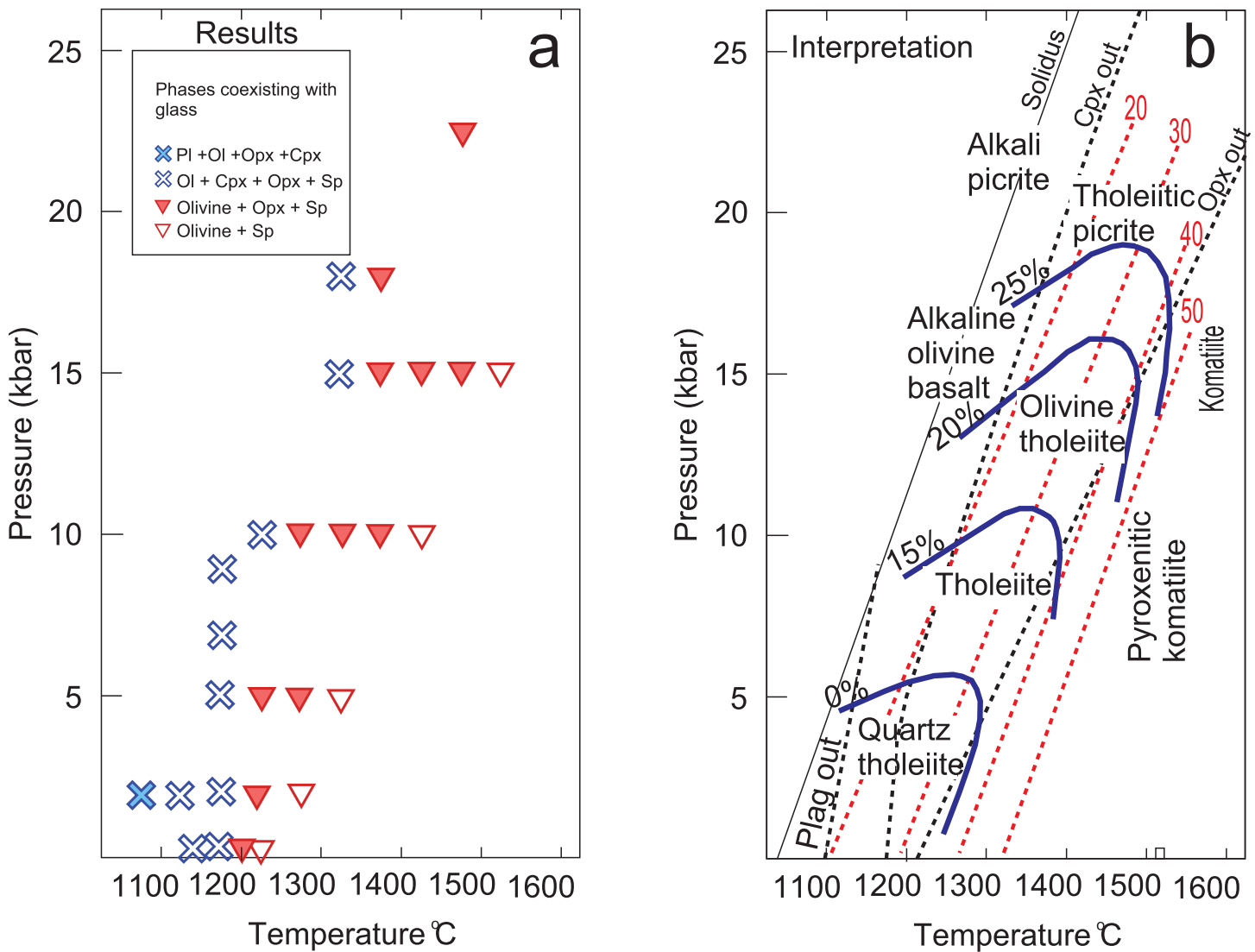
Figure 10 shows the results of their experiments plotted on a  $P$ – $T$  phase diagram. Figure 10a shows only the experimental results with no interpretation. Figure 10b shows the interpreted diagram. It shows that once the solidus is crossed that there is a progressive loss of phases with increasing temperature. The first phase to be completely melted is clinopyroxene, which is followed by orthopyroxene. Spinel and olivine are stable at the highest temperatures. Overlain on the interpreted phase relations in Figure 10b are the percentages of melting and curves showing the amount of normative olivine in the melts as well as approximate ranges of pressure and temperature for different magma compositions. Alkaline magmas are produced by the smallest degrees of partial melting, i.e. near the solidus. Increasing pressure increases the amount of normative olivine in the melt causing a transition in melt composition from quartz tholeiite to tholeiitic picrite.

Data on the phase relations of partial melting of anhydrous peridotite have been used to develop models that allow calculation of the volume and composition of magma generated by decompression and extension of oceanic lithosphere (McKenzie and Bickle 1988), as well as to assess the degree of melting of peridotite dredged from mid-ocean ridges (Dick et al. 1984). Most recently, Jaques and Green's (1980) experimental results have been used by Bénard et al. (2017) to develop a petrogenetic model for arc basalts.

### Near Liquidus Crystallization Experiments

Systematic study of simple, synthetic systems led Bowen to develop his reaction series and helped pave the way for a deeper understanding of basalt evolution, in particular the role of the thermal divide that separates the alkaline and tholeiitic basalts (Yoder and Tilley 1962). A classic example of such a study of this type is Bowen's (1912) examination of the binary system Na<sub>2</sub>Al<sub>2</sub>Si<sub>2</sub>O<sub>8</sub> – CaAl<sub>2</sub>Si<sub>2</sub>O<sub>8</sub> (the nepheline – anorthite system). Bowen applied two techniques in this study: the quench method which is described above and the heating curve method. The heating curve method is really a simplified differential thermal analysis, in which a thermocouple is immersed in the composition of interest. As the temperature is decreased, controlled and measured by a second thermocouple, a difference in temperature between the two thermocouples indicates appearance of a phase, because the latent heat released during crystallization is added to the melt. Bowen used this method to determine the general properties of the system but he had to be careful because Day and Sosman (1911) had shown that some for phases, such as feldspar, cooling rate had a major effect on the temperature at which the phase change occurred because the rate of temperature change affects the rate of crystal nucleation.

To avoid this nucleation problem, Bowen used the newly developed quench method to work out the details of the phase diagram. A second reason for using the quench method is that in this method the charges were completely enclosed in platinum which avoided the issue of loss of sodium due to vapourization at the high temperatures of the experiments. For each composition of interest, the samples were held at the



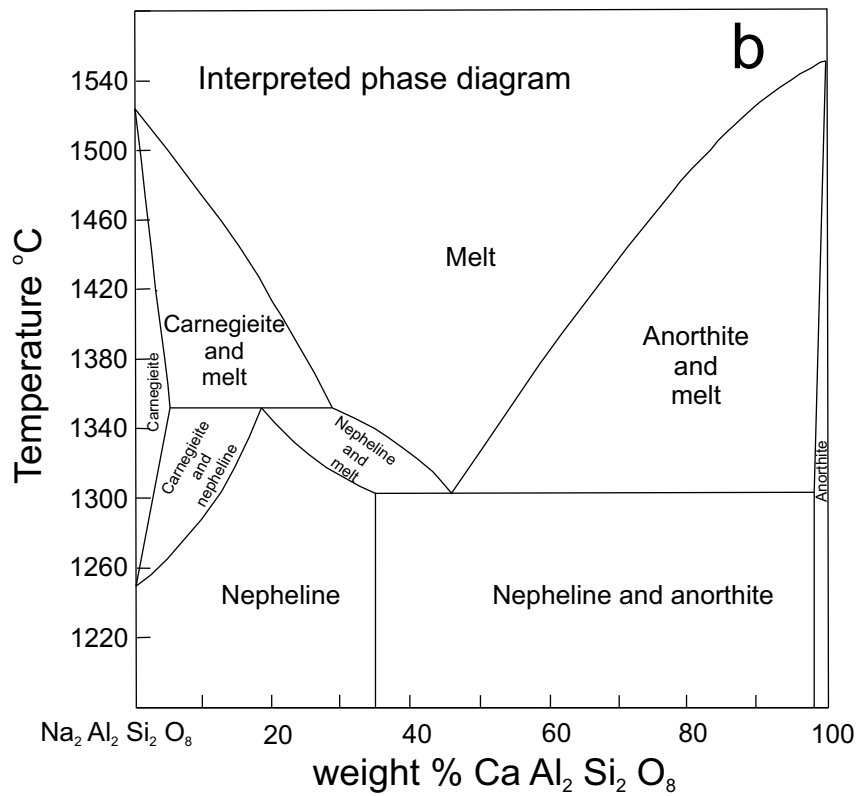
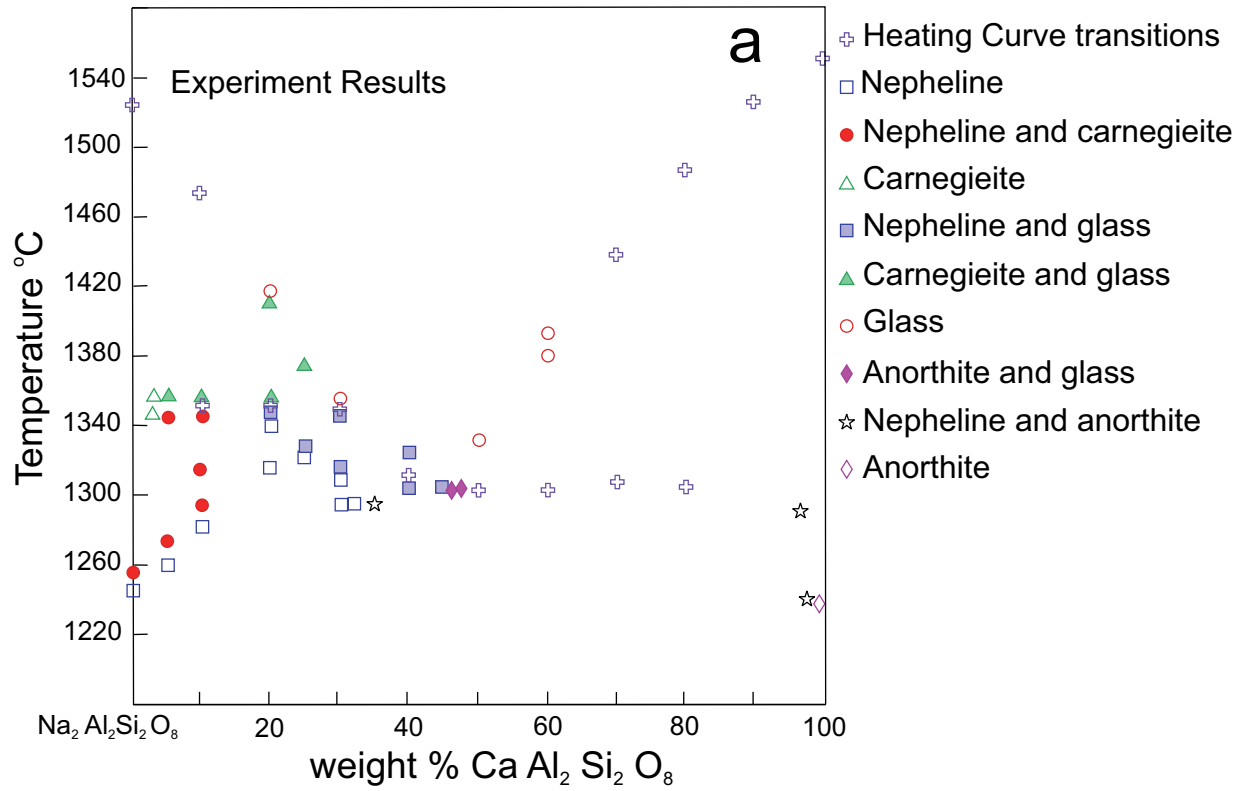
**Figure 10.** a) The results of phase equilibria experiments on pyrolite (Jaques and Green 1980). b) The interpreted phase diagram showing the solidus and mineral out lines. Dotted line with numbers indicates the percentage of melt present in the experiments. The solid lines with percentages show the amount of normative olivine in the melt. Cpx - clinopyroxene, Pl - plagioclase, Ol - olivine, Opx - orthopyroxene, Sp - spinel.

desired temperature for at least an hour, though some of the experiments had to be held at the run temperature for several days to ensure nucleation and crystallization under equilibrium conditions. Given the technology of the day and the banks of resistors that were used for temperature control, this must have presented significant challenges. At the end of each experiment, the platinum wrapped charges were opened and the contents crushed and examined under the microscope to allow identification of the phases.

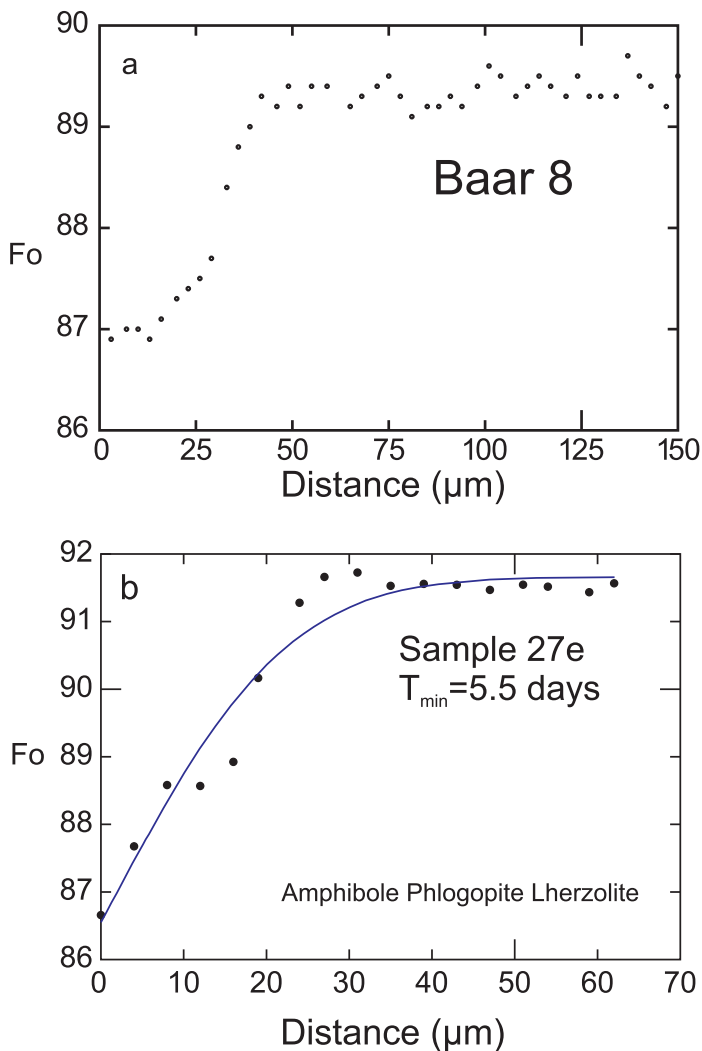
Overall Bowen did 'several score' experiments, the results of which are plotted in Figure 11. The top diagram in this figure is the 'raw' phase diagram with only the data and no interpretation. The bottom is the phase diagram we are more used to seeing – a complete map of the phase boundaries with no experimental information given. It is interesting to note that portions of the phase diagram calculated using independently determined thermodynamic data give very close reproductions of the diagram produced by Bowen.

### What Are The Transport Times for Mafic Magmas From Source To Eruption?

This is a critical question for volcanologists interested in making eruption predictions at dormant volcanoes. The natural samples that help to answer the question must preserve reactions that have not reached equilibrium because these potentially preserve information on reaction time in the form of compositional zonation or reaction rim growth. As an example of such reactions, Shaw and Klügel (2002) examined peridotite xenoliths that have zoned olivine in contact with basaltic melt. They measured the compositional variation in the olivine crystals with the electron probe (Fig. 12a), but could not determine how long the zoning took to develop without access to experimental data. Zoning can develop during growth or as a mineral re-equilibrates with magma. Shaw and Klügel (2002) showed that olivine was a stable liquidus phase in the lavas they examined. This meant that the olivine in the peridotites, which has a much higher forsterite content than the liquidus olivine,



**Figure 11.** a) The results of Bowen's experiments on the  $\text{Na}_2\text{Al}_2\text{Si}_2\text{O}_8$ – $\text{CaAl}_2\text{Si}_2\text{O}_8$  system showing the position of transitions defined by the heating curve method and the phases present in long duration quench experiments (Bowen 1912). b) The interpreted phase diagram with no experimental results shown. This is typically the way that phase diagrams are presented to students.



**Figure 12.** a) A compositional profile in olivine in contact with basaltic melt (Shaw and Klügel 2002). b) A diffusion profile in olivine from the Rockeskyllerkopf volcano in the West Eifel region of Germany (Lebert 2012). The curve shows a binary diffusion model for the profile that was calculated using the experimental data of Chakraborty (1997).

had to undergo re-equilibration. The only way for this to occur is via interdiffusion of iron and magnesium between olivine and liquid.

There are two unknowns in even the simplest diffusion equation (see Zhang 2008 for examples), namely, time and the diffusion coefficient ( $D$ ). If we know the duration of interdiffusion, we can solve for  $D$  and vice versa. To determine  $D$ , we must perform a diffusion experiment for a known duration and ensure that we quench before equilibrium is attained, in order to preserve the compositional gradients developed during the experiment.

Experiments with crystals or melts can give us the value of  $D$  as a function of temperature, oxygen fugacity, pressure, etc. (Zhang and Cherniak 2010). A particularly well designed experimental study of diffusion that is relevant to the example above, is that of Chakraborty (1997) who set out to determine the interdiffusion coefficient of Fe and Mg in olivine. This had been examined by two other groups in the 1970's but there was

significant variability in the determined diffusion coefficients (Buseck and Buseck 1973; Misener 1974). Chakraborty's experiments were designed to allow an examination of the diffusion coefficient as a function of crystallographic orientation and temperature. The experimental method is quite simple: place oriented crystals of olivine of different composition in contact and anneal them at the desired temperature and oxygen fugacity, paying close attention to the duration of the experiment. Chakraborty performed 14 experiments that ranged in duration from 2 to 15 days in which he controlled the orientation of the crystals, temperature and oxygen fugacity. Although the experiments themselves are quite simple, the determination of the diffusion coefficients is more complex and beyond the scope of this review. The final result of the experimental study was an equation that allowed calculation of the diffusion coefficient of Fe/Mg in olivine as a function of temperature and orientation. Figure 12b shows an example of a modelled compositional profile in an olivine from a peridotite xenolith from the West Eifel volcanic field (Lebert 2012). A model profile has been fitted to the data using an estimate of the temperature and oxygen fugacity during transport. This shows that the olivine was in contact with its transporting magma for around 5 days. Since the xenoliths were entrained at a depth of around 50 km this gives an average ascent rate for the magma of around 0.5 km/h.

Numerous studies have used Chakraborty's data to model diffusion profile in olivine in order to extract magma–melt contact times and develop models of magma ascent and magma chamber dynamics (Jankovics et al. 2013; Kahl et al. 2015; McGee et al. 2015; Marchev et al. 2017). Clearly, answering these questions in the absence of experimental data would have been impossible.

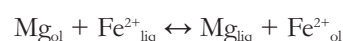
### How Do Melting and Crystallization Influence the Behaviour of Major and Trace Elements?

To answer this question we need to determine whether the element of interest is concentrated in the mineral phase or the melt, i.e. we need to determine its partition coefficient. For some elements we can make a qualitative assessment of this behaviour using simple phase diagrams. For example, from the phase diagram of the  $Mg_2SiO_4$ – $Fe_2SiO_4$  system we can see that olivine crystallizing from any melt that has a composition between the two end members will always be more magnesian than the melt. This behaviour leads to the well-known iron-enrichment trend that is typical of tholeiitic systems.

#### Olivine/Melt Equilibria

Roeder and Emslie (1970) made a quantitative study of the relative partitioning of iron and magnesium between olivine and melt. Their goal was to use partitioning data to estimate the location of the olivine saturation surface in basaltic melts in temperature–composition space and to use olivine and co-existing glass compositions to estimate magmatic temperatures.

The distribution of Fe and Mg is controlled by the reaction:



If an equilibrium constant can be defined for this reaction, the composition of olivine can be used to predict the composition of the equilibrium liquid and crystallization temperature. One of the difficulties in dealing with the distribution of major elements between minerals and melts, as opposed to trace elements, is that some assumptions have to be made regarding the ideality of the system under study. In their work, Roeder and Emslie considered the liquid and solid solution to be ideal, in which case the activities of FeO and MgO could be replaced by the mole fraction of components in solid and liquid to calculate the equilibrium constant, i.e.

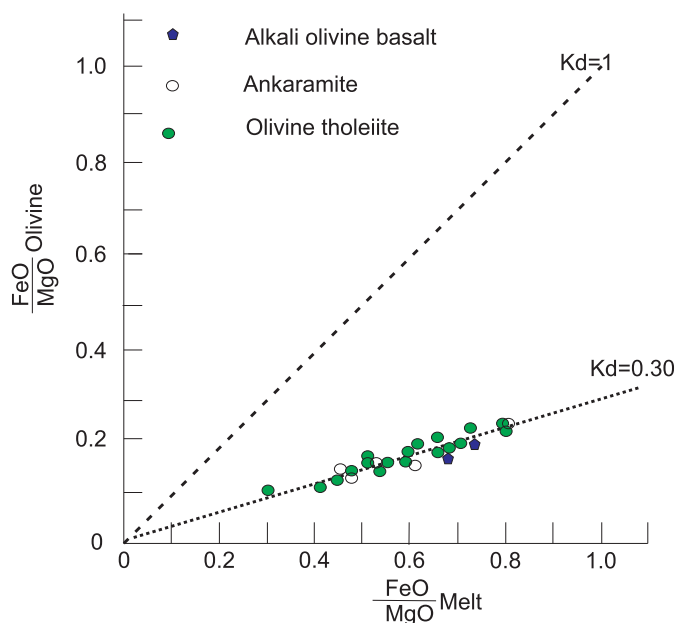
$$K = X_{ol}^{FeO} / X_{liq}^{FeO} * X_{liq}^{MgO} / X_{ol}^{MgO}$$

They used three different natural basalts from Hawaii that were encapsulated in either platinum, silver–palladium or alumina depending on the temperature and  $fO_2$ . Oxygen fugacity was controlled with mixtures of carbon dioxide and hydrogen and calibrated against the Fe–FeO and Ni–NiO reactions. They measured and controlled temperature with a type-S thermocouple and ran their experiments for a minimum of two days. They did not comment on the possibility of iron loss in their runs and the only discussion of the extent of equilibrium is that the minimum of 2 days was “... found to be sufficient for equilibrium” since it confirmed the results of earlier workers. In hindsight it appears that they were correct as the numerous measurements that have followed (e.g. Toplis 2005) have confirmed their results.

They reported on 44 experiments at one atmosphere at 1150–1300°C and controlled  $fO_2$  and used their data (Fig. 13) to define the value of  $K$  as  $0.30 \pm 0.03$ . The partitioning model was updated to include the effects of pressure, water content and liquid composition by Toplis (2005). Roeder and Emslie’s results have been used in more than 1800 published studies. Their partitioning model is commonly used to assess the degree of equilibration of phenocrysts with their host magma or to calculate the degree of fractionation of a magma from the composition of olivine in cumulates. This work was also one of the first to use mineral – melt equilibria as a geothermometer and its influence is shown in the work of Putirka (1997) and Putirka et al. (1996, 2003) who have been developing a wide variety of mineral – melt thermometers using a similar approach.

**Trace Element Partitioning**

The partitioning behaviour of trace elements is used to model fractionation of magmas (Shaw 1970; Allègre and Minster 1978; Minster and Allègre 1978), or derive magma compositions from mineral chemical data (e.g. Shaw and Eyzaguirre 2000). In the early days of trace-element analyses, most measurements of partition coefficients were made on phenocryst–groundmass pairs in natural volcanic rocks. The authors of these studies recognized that there were potential limitations on their accuracy as the phenocrysts are assumed to be *in situ* and are commonly zoned and therefore may only preserve a local equilibrium with the groundmass. In addition, later studies noted that heterogeneous nucleation and crystallization



**Figure 13.** The experimental results of Roeder and Emslie (1970) showing the composition of olivine and coexisting melt for three different basalts over a range of temperatures. The best fit to the data gives the partition coefficient for Fe/Mg between olivine and melt.

during quenching can produce rims on the minerals that are not in equilibrium with the groundmass.

There has always been a need for high quality partitioning data for a wide variety of mineral and melt compositions. This need is compounded by the observation from phenocryst–groundmass compositions that partitioning behaviour varies with melt composition. The consequence is the development of a large database of high quality partitioning data from experimental studies (see <https://earthref.org/GERM/>) that supports trace-element modelling in igneous rocks. However, there are still some significant holes in the database – particularly for unusual compositions such as komatiite, carbonatite and kimberlite. Furthermore, the theoretical understanding of partitioning that has been gained from these studies has led to predictive models of partitioning behaviour (Blundy and Wood 1994; Blundy and Dalton 2000; van Westrenen et al. 2000).

**Trace Element Partitioning Experiments**

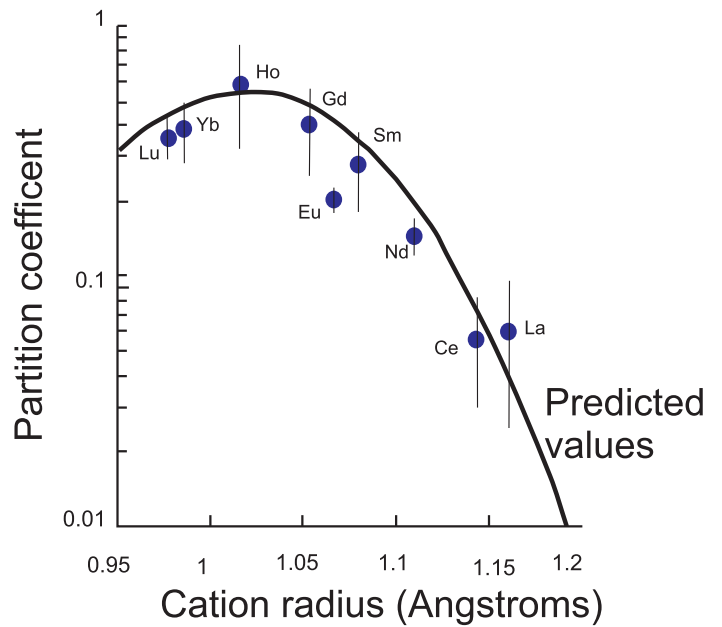
As is the case with the major elements, the change in trace element partitioning experiments must reach equilibrium. Calculation of the partition coefficient is less complex than for major elements because no assumptions have to be made about the thermodynamic ideality of partitioning. The composition of element  $i$  in the mineral is linearly related to the concentration of  $i$  in the melt, i.e. the Henry’s law region (see Jones 2016 for a detailed treatment).

A widely used study of this type is that by Hart and Dunn (1993) who examined the distribution of 24 trace elements between clinopyroxene and alkali basalt at 1380°C and 3 GPa in an attempt to resolve large discrepancies in measured values for different clinopyroxene–melt pairs in previous studies. Although the study was not able to fully resolve the issues with

the earlier work, it has become an important basis for developing and testing models of partitioning behaviour from the elastic moduli of the minerals of interest (Blundy and Wood 1994). The experiments used a fused chip of a natural basalt placed in a graphite capsule and heated to 1380°C at 3 GPa in a piston-cylinder press. Temperature was monitored by a type R thermocouple and pressure was calibrated against the melting point of NaCl. The experiment charge was not ideal for determination of partitioning behaviour; it comprised two large, zoned clinopyroxene crystals with rims of quench crystals in a matrix of glass, some of which had quench crystallized. The zonation of the clinopyroxene suggests that the charge did not fully equilibrate, though the authors suggest that the zonation represents growth zoning. They used earlier experimental data to argue that the inner zones of the clinopyroxene grains were in equilibrium with the melt and that the outer zones resulted from rapid growth under disequilibrium conditions controlled by the rate of interface attachment. This study shows that even in the controlled world of the experiment, it may not be easy or simple to interpret the results. Interestingly, despite the apparent problems with the experiments, the results of Hart and Dunn (1993) have been confirmed in predictive models of partitioning based on other experimental data (Blundy and Dalton 2000). This latter study is working toward the ultimate goal of a predictive model for partitioning that will account for pressure, temperature, melt composition, oxygen fugacity, volatile content and other intensive variables (Fig. 14). It would appear that the ultimate goal of the experimental petrologist is to put themselves out of work.

### What Controls the Eruption Styles of Basaltic vs Andesitic/Dacitic Volcanic Systems?

The differences in the flow characteristics of basaltic vs more silicic magmas are quite obvious, i.e. widespread basaltic flows vs lava domes and spines. Similarly, the effects of temperature on the flow characteristics of basalt can be seen in the transition from pahoehoe to aa flow (Kilburn 1981). The main parameter that controls the flow characteristics of lava is viscosity and since the late 1960's geologists have been interested in finding the relations between magma composition, temperature and viscosity. Shaw (1969) described how the viscosity of a magma can be measured using a concentric cylinder viscometer. This is a common technique that is used to measure the viscosity of oil, paint and other liquids. A spindle is inserted into the liquid whose viscosity is to be determined. The liquid is held in a cylindrical cup and the spindle is rotated at a constant speed and the torque on the spindle is measured. The torque readings and the angular velocity of the spindle can then be used to calculate the viscosity. Viscosity determination at room temperature uses steel spindles and glass cups. Measurements on magma, at temperatures often greater than 1000°C, requires careful choice of materials since they should be strong enough to deal with the applied torque at the temperature of the experiment and should also be unreactive with the liquids to be measured. Temperature control is of particu-



**Figure 14.** Experimental data of Hart and Dunn (1993) and a model curve calculated using the method of Blundy and Wood (1994). There is close agreement between the measured partitioning values.

lar importance in these measurements, since viscosity varies significantly with temperature.

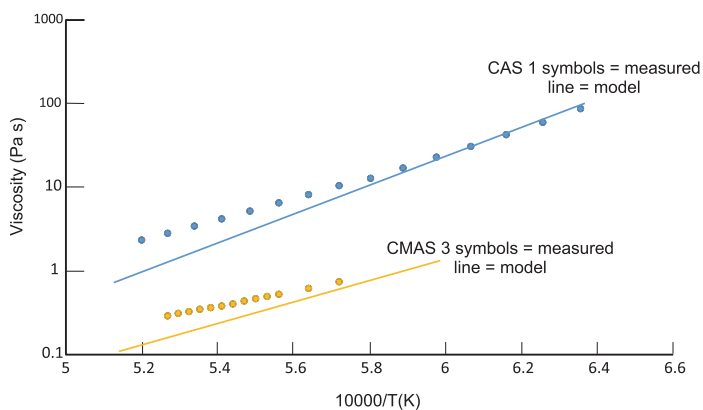
Shaw's (1969, 1972) systematic experiments on natural compositions using melted samples of erupted materials led to the first empirical model of melt viscosity (Bottinga and Weill 1972). However, it did not take long for geoscientists to apply a Bowen-esque approach to the viscosity problem by examining how changes in composition in simple systems affect viscosity (Scarfe and Elderfield 1975; Scarfe 1977a, b; Dingwell et al. 1985; Mysen et al. 1985; Dingwell 1989, 1992; Webb 1991). After several decades of intensive research, we now have models that can be applied to any natural composition at any temperature above the liquidus (Hess et al. 1996; Giordano and Russell 2007; Giordano et al. 2008). Furthermore we have a much deeper understanding of the physics of silicate melts that is helping volcanologists to understand how magma behaves before and during eruption. Figure 15 shows a comparison of measured viscosities in two simple melts and the results of one of the viscosity models. There is extremely good agreement between the two.

Viscosity data are essential in developing models of magma transport and eruption and in the dynamics of lava flows. An excellent example of how viscosity data have been used in interpreting the genesis of real rocks is Holness et al. (2017a) in which they use viscosity data to model the settling and fluid dynamics of cumulate formation in a layered intrusion.

### THE FUTURE OF EXPERIMENTAL PETROLOGY

Some aspects of experimental petrology as it relates to the igneous rocks have advanced to the point where we now have robust models that can predict phase equilibria or the physical properties of a magma. In other fields, we are still collecting the basic data that we need to build models, e.g. for partition-





**Figure 15.** Viscosity measured by rotational viscometry (points) for two synthetic melts in the CaO–Al<sub>2</sub>O<sub>3</sub>–SiO<sub>2</sub> (CAS) and CaO–MgO–Al<sub>2</sub>O<sub>3</sub>–SiO<sub>2</sub> (CMAS) systems (Shaw 2006) compared to the viscosity calculated using the model of Giordano and Russell (2007).

ing between minerals and melts as a function of pressure, temperature, melt composition, oxygen fugacity, etc., but we are quite a long way down the road since preliminary models have been proposed.

A major focus of experimentalists should be to help in understanding the origins of microstructure in igneous rocks. Much of what we ‘know’ about rock microstructure has never been experimentally tested (Vernon 2004). Despite more than 100 years of study, there is still significant debate over the role of crystal accumulation, demonstrated by Bowen and developed into a model to explain layered intrusions (Wager and Brown 1967) vs subsolidus processes in the development of igneous layering even in such classic localities as the Skaergaard intrusion in East Greenland (Holness et al. 2017b). The methods of experimental petrology, in particular experiments in dynamic magmatic systems, will be of critical importance in solving this long standing problem.

There are still phase equilibrium experiments to be done. Though we understand much of the phase relations of the common magmas, the genesis and crystallization behaviour of more exotic compositions such as kimberlites, lamproites and carbonatites requires further study. In addition, the roles of volatiles other than water and carbon dioxide need to be better understood, particularly in alkaline magmas such as those found in the Roman Volcanic Province, which is currently entering a new period of unrest in the Phlegrean fields region (Chiodini et al. 2016). This work will need close coordination between the thermodynamic modelling and experimental petrology communities. The experiments will need to be focused on the areas where critical information is needed to extend the existing models to more exotic composition.

The growing populations around active volcanoes means that we need to have a better understanding of the properties of magma chambers and their contained magma, crystal mushes and the bubble-rich magmas that form as they decompress. As well as continued study of physical properties, experimental petrologists need to scale up experiments so that small scale magmatic systems can be constructed and studied in the laboratory. Some of this work is already in progress, for exam-

ple, Rager et al. (2014) report on experiments that simulate explosive fragmentation of magma during an eruption. However, there is still a need for experimental data on magma behaviour under magma chamber conditions.

Really the future of experimental petrology lies in the hands of petrologists themselves. Imagine a field problem and an experiment can likely be designed to help understand it. All you need to do is contact your nearest experimental petrologist!

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# SERIES



## Economic Geology Models 2. Tantalum and Niobium: Deposits, Resources, Exploration Methods and Market – A Primer for Geoscientists

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### SUMMARY

The world's main tantalum (Ta) resources are in pegmatites (e.g. Wodgina, Australia), rare element-enriched granites (e.g.

Abu Dabbab, Egypt), peralkaline complexes (e.g. Nechalacho, Canada), weathered crusts overlying the previously mentioned deposit types, and in placers. Niobium (Nb) resources with the highest economic potential are in weathered crusts that overlie carbonatite complexes (e.g. Catalão I and II, Brazil). Brazil accounts for 90% of the global Nb mine production with another 9% coming from the Niobec Mine, Canada (a hard-rock underground mine). However, at least 17 undeveloped carbonatite complexes outside of Brazil have NI-43-101 compliant Nb resource estimates (e.g. Aley carbonatite, Canada). Concentrates from most carbonatites are used to produce ferri-niobium (Fe–Nb alloy), and Ta is not recovered. The Ta and Nb contents of some carbonatites (e.g. Upper Fir deposit and Crevier dyke, Canada) are of the same order of magnitude as that of pegmatite ores; however, concentrates from carbonatites have a higher Nb/Ta ratio. Historically, 10–12% Ta<sub>2</sub>O<sub>5</sub> in Nb concentrates has not been recovered in ‘western’ smelters because of the hydrofluoric acid cost. Western countries perceive Ta and Nb supplies to be at risk. Tantalum market downturns resulted in several mines in Australia and Canada closing, at least temporarily, and a resultant shortfall has been filled by what is now recognized as ‘conflict-free columbite-tantalite’ from Central Africa. The lack of ore will not be a key factor in future Ta and Nb supply disruption. For example, more than 280 Nb- and 160 Ta-bearing occurrences are known in Canada alone, and more resources will likely to be discovered as geophysical and geochemical exploration methods are optimized.

### RÉSUMÉ

Les principales sources mondiales en tantale (Ta) sont les pegmatites (par ex. Wodgina, Australie), les granites enrichis en éléments rares (par ex. Abu Dabbab, Égypte), les complexes hyperalkalins (par ex. Nechalacho, Canada), les croûtes altérées recouvrant les types de gisements déjà mentionnés, et les placers. Les sources en niobium (Nb) ayant le meilleur potentiel économique se trouvent dans les croûtes altérées qui recouvrent les complexes de carbonatite (par ex. Catalão I et II, Brésil). Le Brésil est la source de 90% de la production minière mondiale de Nb, et 9% provient de la mine Niobec, au Canada (une mine souterraine). Cela dit, il existe au moins 17 complexes de carbonatite non développés à l'extérieur du Brésil dont les estimations de ressources en Nb sont conformes à la norme NI-43-101 (par ex. Aley carbonatite, Canada). Les concentrés de la plupart des carbonatites sont utilisés pour produire du ferri-niobium (alliage Fe-Nb), et le Ta n'est pas récupéré. Les teneurs en Ta et Nb de certaines carbonatites

(par ex. le gisement de Upper Fir et le dyke Crevier, Canada) sont du même ordre de grandeur que celles des minerais de pegmatite; cependant, les concentrés de carbonatites ont une proportion Nb/Ta plus élevée. Historiquement, 10 à 12% du  $Ta_2O_5$  des concentrés de Nb n'ont pas été récupérés dans les fonderies de l'Ouest en raison du coût de l'acide fluorhydrique. Les pays occidentaux estiment que les approvisionnements en Ta et Nb sont à risque. Le fléchissement du marché du tantale a entraîné la fermeture, au moins temporaire, de plusieurs mines en Australie et au Canada, et la pénurie qui en résulte a été comblée par ce qui est maintenant reconnu comme étant du minerai de colombite-tantalite «sans conflit» d'Afrique centrale. Le manque de minerai ne sera pas un facteur clé des perturbations à venir de l'approvisionnement en Ta et Nb. Par exemple, plus de 280 occurrences minérales contenant du Nb et 160 occurrences minérales contenant du Ta sont connues au Canada seulement, et davantage de ressources seront probablement découvertes à mesure que les méthodes d'exploration géophysique et géochimique seront optimisées.

*Traduit par le Traducteur*

## INTRODUCTION

Tantalum (Ta) is used largely in capacitors for automotive electronics, mobile phones, and personal computers, as well as in glass lenses, and as Ta-carbide in cutting tools. The main uses of niobium (Nb) are High-Strength Low-Alloy (HSLA) steels and super alloys for the aerospace industry (Roskill Information Services 2016).

Tantalum and Nb are commonly considered strategic and critical materials in modern society (Simandl et al. 2015, and references therein). However, lists of critical materials vary to a large extent on the priorities and objectives of the organization that commissions the study (Simandl et al. 2015, and references therein). For example, both Ta and Nb are considered critical by the most recent assessment ordered by the European Commission (2017). The level of criticality of an assessed commodity is based on a combination of: 1) its importance to the economy of the European Union, and 2) an estimate of the level of risk associated with their supply chain. To quantify supply risk, the European Commission relied on the World Governance Indicator (WGI). The WGI includes factors such as voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law, and control of corruption (European Commission 2017). Tantalum and Nb are also on the newest criticality list in United States of America (USGS 2018).

In general, projects involving critical materials are popular with investors. Niobium and Ta grade, the  $Ta_2O_5$  / [ $Ta_2O_5$  +  $Nb_2O_5$ ] ratio of the concentrate, tonnage, mineralogy, and permissive metallurgy are some of the key technical factors that are used to screen and rank potential development projects. However, since Ta and Nb are considered strategic for the economy and national security of many industrialized countries, governmental interventions will perturb any project ranking based strictly on technical and economic parameters.

## OVERVIEW OF GEOLOGY OF Nb AND Ta DEPOSITS

The world's main primary Ta resources are contained in pegmatite-related deposits (e.g. Wodgina: Li, Ta, Australia; Mibra: Ta, feldspar, Sn, Brazil; and the historic but now depleted Tanco deposit: Ta, Cs, Li, Canada); rare element-enriched granites (e.g. Yichun, China; Beauvoir, France), and in peralkaline granite complexes (e.g. Nechalacho: REE, Nb, Ta, Zr, Canada; Al Ghurayyah: Ta, Nb, Saudi Arabia). Important resources also exist in weathered crusts overlying the previously mentioned hard-rock deposit types, and in placer deposits where Ta may be a co-product of tin (Mackay and Simandl 2014a; Linnen et al. 2014; Burt 2016). Weathered crusts are preferred to hard-rock deposits because weathering liberates Ta-bearing minerals and no blasting, crushing or grinding are required. In this respect, Ta production from weathered crusts differs from the processing of similar materials for Nb extraction (see below).

Globally, most Nb resources are contained in carbonatite complex-related deposits (e.g. Catalão I and II and Araxá, Brazil; Aley carbonatite and Niobec Mine, Canada) and peralkaline intrusions where Nb commonly coexists with rare earth element (REE) mineralization (Simandl 2014; Mackay and Simandl 2014a). Because of high grades and relatively simple metallurgy, most of the current Nb production comes from carbonatite complex-related deposits, notably where weathered zones are well developed. The pegmatitic body within the Lovozero peralkaline intrusion in the Kola Peninsula, Russia, is an exception. An estimated six thousand tonnes of loparite [(REE,Na,Ca)<sub>2</sub>(Ti,Nb)<sub>2</sub>O<sub>6</sub>] concentrate containing 30–35% REE<sub>2</sub>O<sub>3</sub>, 8–12% Nb<sub>2</sub>O<sub>5</sub> and 0.6–0.8% Ta<sub>2</sub>O<sub>5</sub> (Zaitsev and Kogarko 2012; Simandl 2014) are produced per year, with light REE being the main product. As with Ta deposits, intense and prolonged weathering of hard-rock carbonatite complex-related deposits has increased the Nb grade and reduced mining and processing costs.

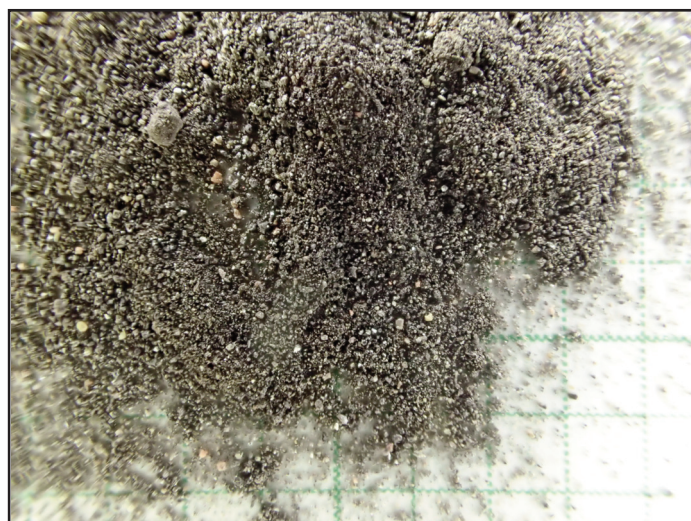
In this review, only carbonatite-related Nb deposits and pegmatite-related Ta deposits are described, because these are the most important deposit types. These two deposit types currently supply the bulk of the world's Ta and Nb requirements. For information on the remaining types of Nb and Ta mineralization listed above, readers are referred to reviews by Linnen et al. (2014) and Mackay and Simandl (2014a).

### Carbonatite-Related Nb (± Ta) Deposits

Carbonatites are defined by the International Union of Geological Sciences (IUGS) as igneous rocks containing more than 50% modal primary carbonates (Le Maitre 2002); however, they may have a metasomatic component. Most carbonatites are spatially associated with one or more of seven intrusive silicate rock groups, including melilitolites, ijolites, alkali gabbros, feldspathoidal syenites, syenites, kimberlites, and lamprophyres and/or their volcanic equivalents (Woolley and Kjarsgaard 2008). This association of rock types is referred to by the general term 'carbonatite complexes' or 'alkaline-carbonatite complexes'.



**Figure 1.** Well-formed pyrochlore crystal from the Ta–Nb-bearing Upper Fir carbonatite deposit, British Columbia, Canada.



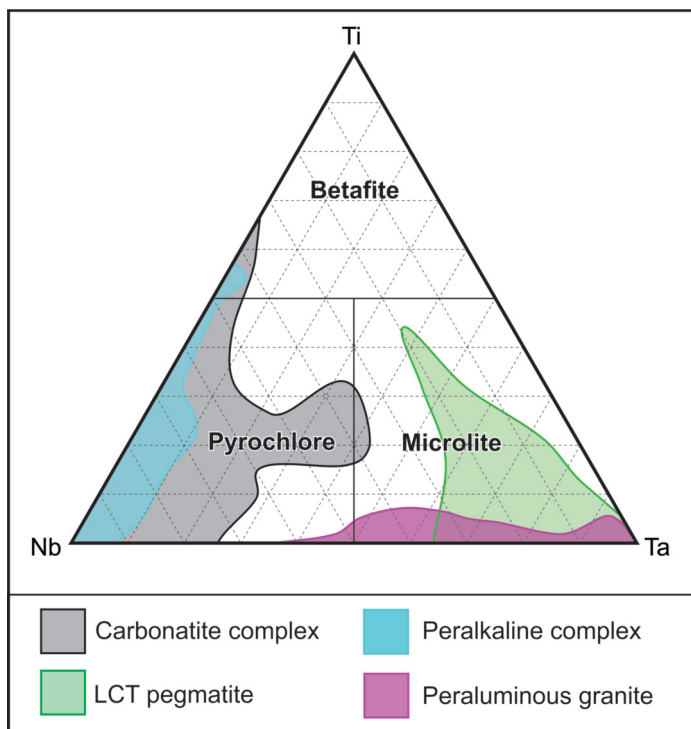
**Figure 2.** Pyrochlore concentrate from the Niobec Mine, St. Honoré carbonatite complex, Québec, Canada. Smallest visible squares on the underlying graph paper are 2 mm in size.

The Nb resources with the highest economic potential are in weathered crusts that overlie carbonatite complexes (e.g. Catalão I and II and Araxá, Brazil). Brazilian carbonatite complexes (weathered and fresh) account for approximately 90% of global Nb mine production, with another 9% coming from the Niobec Mine (a hard-rock underground mine operation) hosted by the St. Honoré carbonatite complex in Québec, Canada (Papp 2017a).

Niobium concentrates from most carbonatite-related deposits are dominated by minerals belonging to the pyrochlore supergroup (Figs. 1 and 2) as defined by Atencio et al. (2010). The composition of three end members may be approximated as follows: pyrochlore [(Na,Ca)<sub>2</sub>Nb<sub>2</sub>O<sub>6</sub>(OH,F)]; betafite [(Ca,U)<sub>2</sub>(Ti,Nb,Ta)<sub>2</sub>O<sub>6</sub>(OH)]; and microlite [(Na,Ca)<sub>2</sub>Ta<sub>2</sub>O<sub>6</sub>(O,OH,F)]. Of these minerals, pyrochlore has the highest Nb content, and microlite has the highest Ta content, whereas betafite is enriched in Ti. Pyrochlore, which is characterized by high Nb and low Ta content (Fig. 3) typifies most carbonatite-derived pyrochlores (Mackay and Simandl 2015; Mackay et al. 2016).

Other common Nb (±Ta) minerals found in carbonatite-related mineralization are columbite-Fe [(Fe,Mn)Nb<sub>2</sub>O<sub>6</sub>], which forms an end member of the solid solution series with tantalite [(Fe,Mn)Ta<sub>2</sub>O<sub>6</sub>], fersmite [(Ca,Ce,Na)(Nb,Ta,Ti)<sub>2</sub>(O,OH,F)<sub>6</sub>] and to a much lesser extent Nb-rich rutile [(Ti,Nb,Fe)O<sub>2</sub>] commonly referred to as ilmenorutile (Mackay and Simandl 2014a). Carbonatite-derived Nb concentrates are mainly used to produce ferroniobium and the associated Ta is not recovered.

In some cases, carbonatites are considered and assessed for Ta and Nb co-production. Examples in Canada include the Upper Fir deposit (indicated resource of 48.4 million tonnes grading 197 ppm Ta<sub>2</sub>O<sub>5</sub> and 1,610 ppm Nb<sub>2</sub>O<sub>5</sub>) and the alkaline pegmatitic dyke within the Crevier carbonatite-syenite complex (indicated and measured resources of 25,369,000 tonnes at 0.2% Nb<sub>2</sub>O<sub>5</sub> and 0.0234% Ta<sub>2</sub>O<sub>5</sub> using the 0.1% Nb<sub>2</sub>O<sub>5</sub> cut-off) (Simandl 2002; Simandl et al. 2002; SGS Cana-



**Figure 3.** Compositional classification of pyrochlore supergroup minerals based on Ta, Nb, and Ti content. Pyrochlore, betafite, and microlite fields as defined by Atencio et al. (2010). Fields of pyrochlore compositions corresponding to carbonatite complexes, peraluminous granites, lithium–cesium–tantalum (LCT) pegmatites, and peralkaline complexes are from Mackay and Simandl (2015).

da Inc–Geostat 2010; Groulier et al. 2014; Kulla and Hardy 2015). In such cases, pyrochlore may have higher Ta content that approaches or reaches the pyrochlore–microlite boundary (Hogarth 1989; Simandl et al. 2002; Chudy 2014; Mackay and Simandl 2015). Such Ta-rich pyrochlores may have higher U content than their Nb-rich equivalents as supported by a positive correlation between Ta and U, and a negative correlation

between Nb and U (Hogarth et al. 2000). The  $Ta_2O_5$  content of mineralization in the Upper Fir and Crevier examples is of the same order of magnitude as that of pegmatite-related deposits from which Ta is being recovered; however, ore mineral concentrates from carbonatite-related deposits have lower  $Ta_2O_5/(Ta_2O_5 + Nb_2O_5)$  ratios than those from pegmatites. Historically, Ta has not been recovered from concentrates containing less than 8 to 12%  $Ta_2O_5$  or those having lower Ta content (Roethe 1989) because the cost of reagents (commonly hydrofluoric acid) exceeds the value of produced Ta and Nb metals in European and North American facilities. The  $Ta_2O_5/(Ta_2O_5 + Nb_2O_5)$  ratios derived from resource calculations for the Upper Fir Carbonatite and Crevier intrusion are 0.122 and 0.117, respectively, suggesting that the  $Ta_2O_5$  content of corresponding concentrates could be of the order of 6 to 8%  $Ta_2O_5$ . This implies that under current market conditions the concept of Ta metal recovery from carbonatite-derived Nb–Ta concentrate may not be realistic unless new and unconventional extraction methods are developed.

### Pegmatite-Related Ta Deposits

For the purpose of this paper, our definition of pegmatite follows very closely the one provided by Neuendorf et al. (2005). Pegmatites are defined as exceptionally coarse-grained igneous rocks (individual crystals  $\geq 1$  cm in size) with interlocking grains. Pegmatites are usually found as irregular dikes, lenses, pods or veins within or near the margins of batholiths, plutons, or in surrounding country rocks. They commonly occur in clusters forming pegmatite fields. The chemical composition of pegmatites approaches that of granite and individual pegmatite bodies may be simple or complexly zoned. For a more comprehensive review of pegmatites, the reader is referred to London (2008). Pegmatites are commonly associated with aplites (related rocks with fine-grained allotriomorphic texture consisting predominantly of anhedral, equant grains). The complex relationship between pegmatites and aplites (massive and layered) is reviewed by London (2014). Tantalum mineralization may be present in both textural varieties but it is most commonly present in fine-grained (aplitic) rocks.

Pegmatites are subdivided into ‘abyssal’, ‘muscovite’, ‘muscovite-rare-element’, ‘rare-element’, and ‘miarolitic’ classes, all of which contain Ta–Nb–Sn minerals (Černý and Ercit 2005; London 2008; Simmons and Webber 2008). The ‘rare-element’ class is strongly enriched in high-field-strength elements (HFSE; e.g. Ta, Nb, Zr, Hf, P) and large-ion lithophile elements (LILE; e.g. Rb, Cs, Li, and Sr). This class of pegmatite has the best exploration potential for Ta. The subdivision of individual classes into subclasses, types, and subtypes is provided and further discussed by Černý et al. (2012).

Most granitic pegmatites, including those belonging to the ‘rare-element class’, may also be subdivided into two distinct families according to trace element signatures (Černý et al. 2012). These two families are either strongly enriched in lithium, cesium, and tantalum (LCT) or enriched in niobium, yttrium, and fluorine (NYF). Pegmatites of the ‘rare-element class’ that also belong to the LCT family are of the most interest to explorers looking for Ta, Li, and Cs. They have a chemical



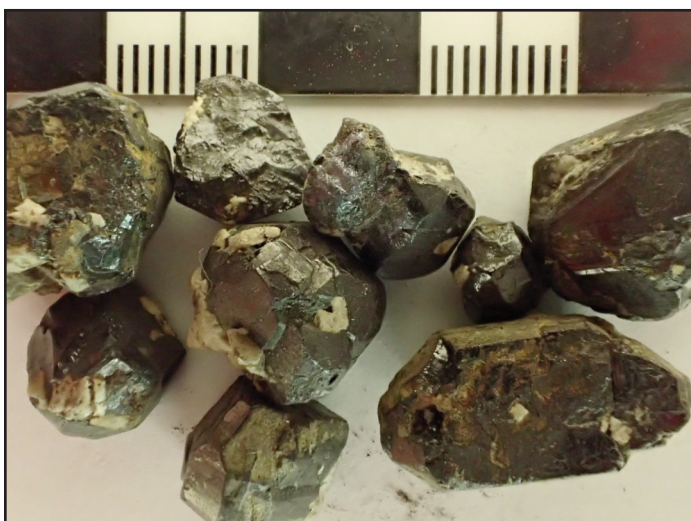
Figure 4. Artisanal mine workings in the pollucite-bearing Urubu pegmatite, Brazil.

affinity with S-type rare-element enriched granites (Černý and Ercit 2005), occur in orogenic settings, and are associated with crustal shortening. They are commonly found adjacent to granitic cupolas or aligned along deep faults (Trueman and Černý 1982). Within the same pegmatite field, the Li, Cs, Be, Ta and Nb content, Ta/Nb ratio, and degree of albitization increase with distance from the parent intrusion (Trueman and Černý 1982). Tantalum enrichment is reflected by Ta-rich oxides and columbite-tantalite series minerals (Černý et al. 2012). Good examples of highly evolved LCT family pegmatites, also belonging to the ‘rare-element class’ are the famous Tanco pegmatite, which historically supplied concentrates of Ta-bearing minerals, spodumene, and pollucite  $[(Cs,Na)_2Al_2Si_4O_{12} \cdot 2H_2O]$  and the Brazilian Urubu pollucite-bearing pegmatite (Fig. 4), which was a historical mica and gemstone producer.

In contrast, mineralization in the NYF family of pegmatites is characterized by oxides and silicates containing heavy rare earth elements (HREE), Ti, U, Th, high concentrations of Nb relative to Ta, and abundant fluorine-bearing minerals (fluorite or topaz). From a practical point of view, the mineralization in these pegmatites is subject to the same metallurgical constraints as that of mineralization from peralkaline intrusions, described below.

Concentrates from most pegmatite-related Ta deposits (both hard-rock and weathered varieties) are dominated by minerals belonging to the columbite-tantalite series (Fig. 5); however, tapiolite  $[(Fe,Mn)(Ta,Nb)_2O_6]$ , wodginite  $[Mn(Sn,Ta)(Ta,Nb)_2O_8]$ , ixiolite  $[(Ta,Nb,Sn,Mn,Fe)O_2]$  and pyrochlore supergroup minerals may be present in smaller amounts (Melcher et al. 2015, 2017). The wide compositional variation of minerals belonging to the columbite-tantalite series derived from pegmatites is shown in Figure 6. The field of columbite-tantalite series minerals from pegmatites covers most of the quadrilateral diagram and nearly coincides with that from peraluminous granites. In contrast to columbite-tantalite series minerals derived from pegmatites, those derived from carbonatites are chemically constrained to a small compositional field



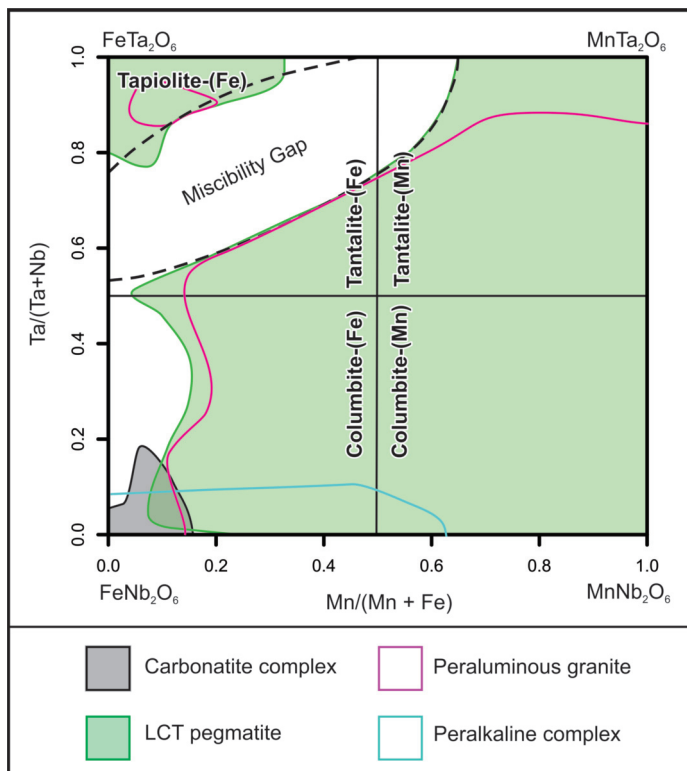


**Figure 5.** Pegmatite-derived columbite-tantalite series mineral from a pegmatite in Pilbara district, Australia. Sample from the School of Earth and Ocean Sciences (SEOS) mineral collection at the University of Victoria, British Columbia, Canada. Large division on the scale is 1 centimetre.

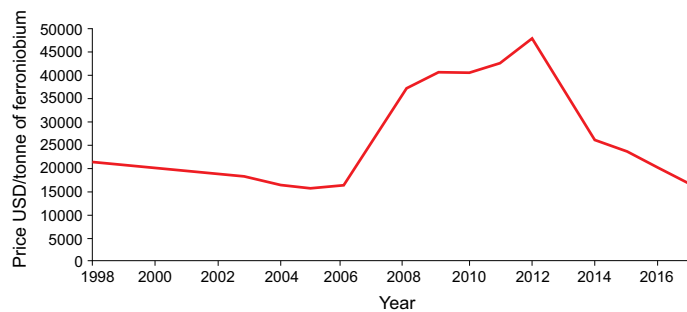
adjacent to the columbite-(Fe) apex with low Ta content. Columbite-tantalite series minerals derived from peralkaline intrusions also have a low Ta content; however, their Mn/(Mn+Fe) ratio is less constrained (Fig. 6). In the ranking of Ta exploration projects for potential development, all other parameters being equal, the higher the  $Ta_2O_5 / (Ta_2O_5 + Nb_2O_5)$  ratio of the deposit, the better its chance of being developed.

**NIOBIUM AND TANTALUM SUPPLY CHAINS**

The fundamentals of the Nb supply chain have not changed significantly during the last 20 years. More than 90% of the world’s Nb production is restricted to a single South American country, Brazil. Worldwide, all major producing Nb mines are highly mechanized and with the exception of the Niobec Mine (St. Honoré complex, Québec, Canada), they are exploited by opencast mining. The world mine production for 2017 was approximately 64,000 tonnes of Nb content (Polyak 2018a). Some important changes that took place in Brazil were linked to more than a fivefold increase in the cost of hydroelectricity from \$25.80 per megawatt-hour to \$147.38 per megawatt-hour in 2015 (Papp 2017c). These price hikes were attributed to the worst drought in 80 years, and the increased energy costs had a significant impact on production costs. Traditionally, most of the Nb product was sold in the form of ferroniobium (rather than concentrate consisting of Nb-bearing minerals) and produced by vertically integrated companies. Consequently, ferroniobium prices are relatively insensitive to global demand (Fig. 7) if compared to other commodities. For example, the 2008–2009 slump in demand had a minimal impact on Nb pricing. The 2016 sale of Anglo American’s Nb and phosphate operations in Brazil to China Molybdenum Co., Ltd. also did not appear to have a major impact on the Nb market; however, since that sale, a larger proportion of concentrate may be shipped to Asia to be transformed into ferroniobium. Despite Nb being considered a critical metal, unless political instability



**Figure 6.** Quadrilateral diagram showing the variability in composition of columbite-tantalite series minerals (from Černý and Ercit 1985). The empirically derived tantalite-tapiolite miscibility gap is from Černý et al. (1992). Compositional fields for columbite-tantalite series minerals from carbonatite complexes, peraluminous granites, lithium–cesium–tantalum (LCT) pegmatites, and peralkaline complexes are from Mackay and Simandl (2015).



**Figure 7.** Historic mass-weighted average US import value of ferroniobium (assuming 65% Nb) for the period 1998 to 2018. Updated from Mackay and Simandl (2014a) based on information contained in US Geological Survey commodity summaries. Prices are adjusted for inflation to 2012 US dollars.

develops in Brazil, any change to the Nb supply chain is expected to be gradual. It remains to be seen if and when some of the more advanced Nb projects outside of Brazil will reach production stage.

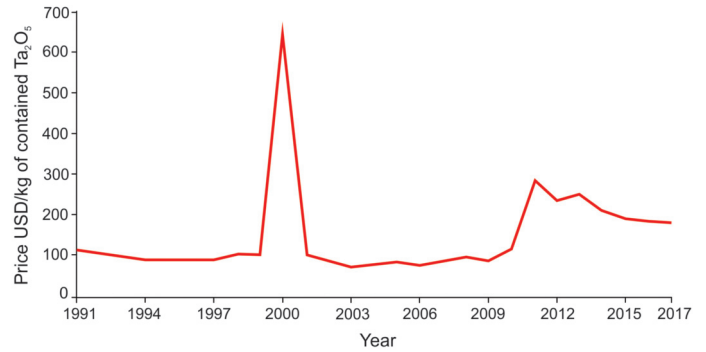
In contrast to Nb, the fundamentals of the Ta supply chain have changed dramatically during the last ten years. As recently as 2007, mechanized mining and processing operations, such as Greenbushes and Wodgina in Australia, Tanco in Canada, and mines in Brazil, China, Ethiopia, and Mozambique (Fig. 8), were producing approximately 75% of the world’s Ta in concentrates, with artisanal production accounting for the rest,



**Figure 8.** Original (circa 2004) industrial-scale processing plant (spiral module 1) at Marropino, Mozambique. The Marropino pegmatite, which was at one time considered as the second largest Ta producing deposit is also well known for gem-quality morganite (pink beryl).

either as columbite-tantalite (colloquially known as ‘coltan’) or as a co-product of tin mining. However, the 2008 stock market meltdown and the mini-recession that followed resulted in a decline in the demand for Ta and lower prices, forcing several of the higher-cost industrial mines off the market, at least temporarily and subsequently forcing increased reliance on generally lower-cost artisanal mines. Notwithstanding a spike in prices from 2010 to 2012, both large Australian mines (Greenbushes and Wodgina) remain closed, at least temporarily, and Tanco has ceased mining Ta ore at its underground mine in Canada. Mechanized mines in Brazil, Ethiopia, Mozambique, China, as well as some new producers in Australia and one in Namibia, continue to operate, but currently account for only approximately 25% of mine production. Artisanal operations, primarily in the Great Lakes Region of Central Africa, West Africa, South America, and Asia, currently account for the remaining 75% (Burt 2016). The world Ta mine production for 2017 was estimated at 1300 tonnes of Ta content (Polyak 2018b).

Larger deposits currently considered for development in industrialized countries, especially those operated by companies listed on Canadian or Australian stock exchanges, require resource and reserve estimates completed in accordance with a regulatory code such as NI 43-101 or Joint Ore Reserves Committee (JORC). The development of such deposits requires pre-feasibility and feasibility studies, and any development is required to comply with applicable environmental regulations. All of this takes time and money; hence, short-term market volatility, typical of specialty metals, prevents most grass-roots discoveries from coming into production in a single attempt. The prospects which were partially developed during the historic Ta price spikes of 1980, 1988, and 2000 (Fig. 9; and Simandl 2002) have existing infrastructure and established resources or reserves, and these have the best chance to be put in production during future Ta price increases. Nevertheless,



**Figure 9.** Price of tantalite reported as US dollars per kilogram of Ta<sub>2</sub>O<sub>5</sub> content for the time period from 1991 to 2018. Updated from Mackay and Simandl (2014a) based on information contained in US Geological Survey commodity summaries. Prices are adjusted for inflation to 2012 US dollars.

there are considerable known resources delineated (Linnen et al. 2014; Mackay and Simandl 2014a) that could be brought into production if longer-term market forces were to render them commercially viable.

Artisanal operations typically exploit soft, weathered crusts overlying pegmatites or related alluvial deposits, and in most cases mining and processing is by hand or uses primitive equipment. Processing of such ores is simple, generally consisting of little more than ground sluicing, such as at Nyabitare in Rwanda (Fig. 10), with further concentration in more central facilities. Consequently, artisanal operations require little or no infrastructure and can be rapidly wound down or reactivated in response to market conditions.

Notwithstanding these inherent advantages, artisanal Ta production has to be regarded as a supply risk. Artisanal miners do not develop mineral reserve or even resource estimates. They follow mineralization until it is exhausted and move on to the next deposit, if available. Furthermore, apart from the documented lax environmental and safety regulations in some of the countries, political and armed-conflict-related risks as well as child labour are also of concern. For decades, ‘conflict minerals’, including Ta, were sourced to a significant extent from conflict areas and proceeds of sales from these and other natural resources did provide some of the funding that helped to perpetuate ongoing conflicts between various fighting factions. However, over the last ten years, the situation has improved significantly due to public pressure and the efforts of end-users (high-technology industries), producers (mining and processing companies), and various governmental agencies in both Ta-producing and Ta-consuming countries. These important initiatives include the Dodd-Frank Act on conflict minerals and artisanal mining issues (USA), which is overseen by US Department of State Foreign Service, and the Directorate General of European Commission’s regulations on conflict minerals. Other contributions include the International Tin Supply Chain Initiative (iTSCi), the Responsible Minerals Initiative (formerly the Conflict-Free Sourcing Initiative), and the efforts of the Tantalum-Niobium International Study Center. A concrete product of these efforts is a list of 40 ‘conflict-free’ Ta smelters established by the Responsible Minerals Ini-



**Figure 10.** Ground sluicing at Nyabitare beryl–Sn–Ta–Nb-bearing weathered pegmatite, producing high grade tantalum–tin concentrate (western Rwanda). Ground sluicing is a simple technique of primary concentration, favoured by artisanal miners, as no power is required.

tiative (<http://www.responsiblemineralsinitiative.org>). However, further measures may be needed to completely eradicate conflict minerals from the Ta supply chain (Pickles 2017).

## LONG-TERM AVAILABILITY OF Ta AND Nb

### Reserves and Resources

From the geologist's point of view, Ta and Nb resources are plentiful. Global Ta 'reserves' were estimated by the United States Geological Survey (USGS) at more than 100,000 tonnes of contained Ta, and most of these 'reserves' are located in Australia (69,000 tonnes of Ta content) and Brazil (36,000 tonnes of Ta content) (Papp 2017b). However, according to the same source, JORC reserves for Australia are only 29,000 tonnes of Ta content. Such apparent discrepancies are due to a wide variety of factors listed and explained in Appendix C of the USGS commodity summaries (USGS 2017). For example, USGS sources include academic articles, company reports, PowerPoint presentations, trade journal articles, etc. Only small portions of these 'resource' and 'reserve' data are likely to be prepared in accordance with NI 43-101 or JORC procedures.

Burt (2009) and the Tantalum-Niobium International Study Center ([www.tanb.org](http://www.tanb.org)), using an extensive but confidential database incorporating most of the world's known deposits, estimated that the 'most likely resource base' (not NI-43-101 or JORC) for contained tantalum exceeded 300,000 tonnes, with Brazil and Australia being the two major sources. Put into perspective, this is over a century of world's Ta needs at the current rate of consumption.

Global Nb 'reserves' were estimated by the USGS at 4.3 million tonnes of contained Nb (Papp 2017a), with most located in Brazil (4.1 million tonnes of contained Nb) and Canada (200,000 tonnes). These estimates are subject to the same uncertainties as the Ta estimates discussed above.

Publicly available information on individual Nb and Ta deposits was compiled by Mackay and Simandl (2014a). Niobium and Ta grade-tonnage diagrams presented in this study are based on that information with minor updates (Fig. 11a, b). Unfortunately, as is the case in former studies, many of the resource estimates were not done in accordance with NI 43-101 or JORC guidelines and some of the deposits such as Tanco (Canada) may be almost completely mined out. Furthermore, many small deposits (weathered crusts overlying pegmatites and placers) that currently supply approximately 75% of tantalite-columbite concentrate are not shown because the grade and tonnage data are unavailable. Nevertheless, these diagrams are extremely useful for comparing the relative importance of the main Nb and Ta deposit types. They show that Nb- and Ta-containing deposits vary widely in terms of grade and tonnage (note that the spacing between isotonnage lines is logarithmic). The highest Nb<sub>2</sub>O<sub>5</sub> grades and tonnages correspond to weathering-enriched carbonatite complex-related deposits (e.g. Araxá, Catalão I and II and Seis Lagos, Brazil) followed by hard-rock carbonatite-related deposits (e.g. Aley and Niobec Mine, Canada). Peralkaline-granite-related deposits also represent significant tonnages of contained Nb<sub>2</sub>O<sub>5</sub> (e.g. Lovozero, Russia and Nechalacho, Canada). The highest Ta<sub>2</sub>O<sub>5</sub> grades shown in Figure 11b correspond to pegmatites (e.g. Tanco, Canada; Morruea, Mozambique; and Wodgina, Australia). A large proportion of Ta resources is contained in a few large, relatively low-grade undeveloped peralkaline intrusion-hosted deposits (e.g. Ghurayyah, Saudi Arabia; Nechalacho, Canada).

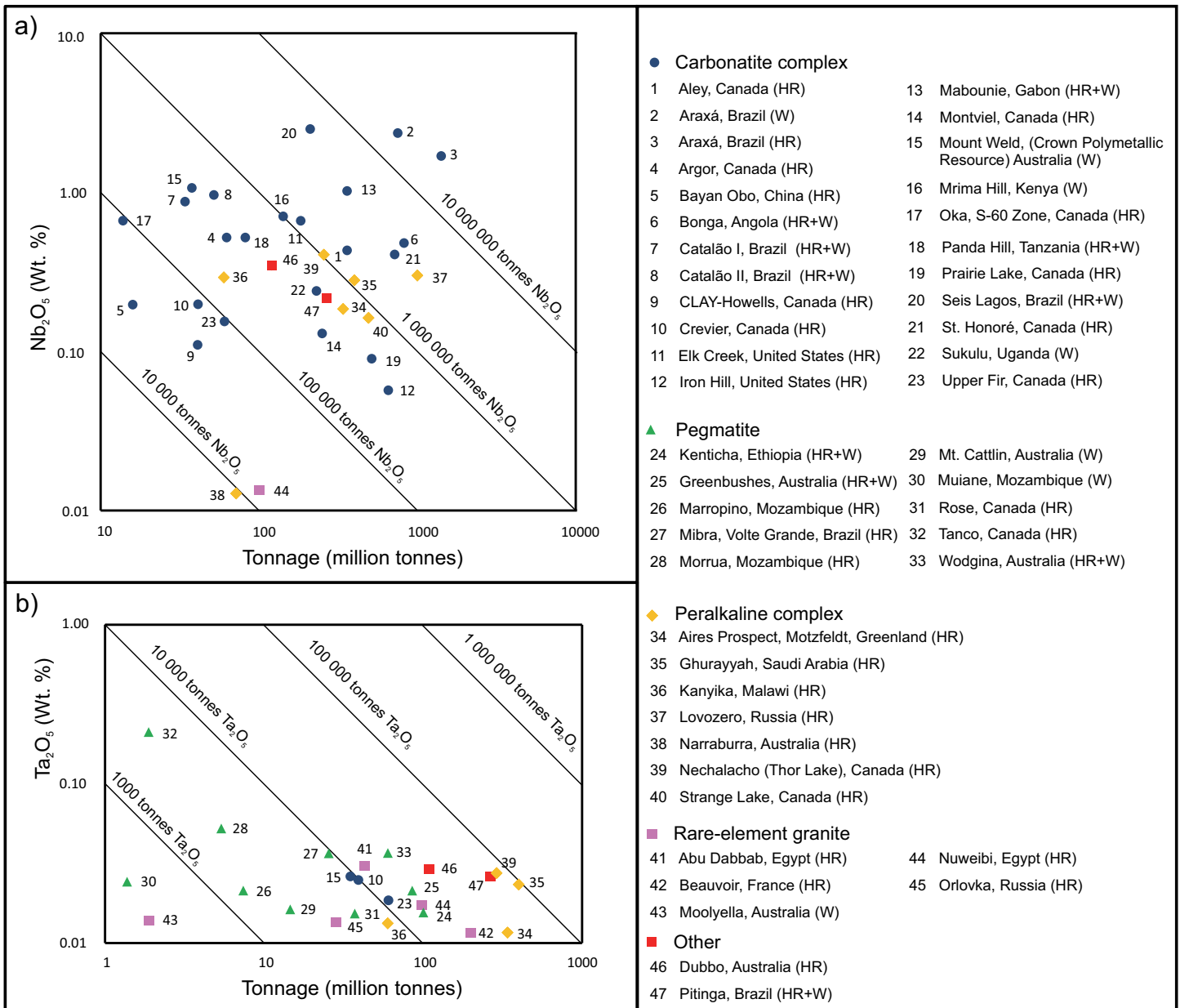
Regardless of the accuracy of the above estimates, a global lack of ore will not be a key factor in any future supply disruption, as long as market forces can absorb the likely (if not inevitable) long-term reduction in tantalum ore grades and probable subsequent increased costs of production.

### Additional Factors Relevant to Long Term Availability of Ta and Nb

Numerous small Ta-bearing pegmatites form clusters in north-eastern Brazil, Colombia, Bolivia, Namibia, southern Russia, south-east Asia, India, USA, and Canada (Burt 2016). More than 280 Nb- and 160 Ta-bearing occurrences (Figs. 12 and 13) are known in Canada alone (Simandl et al. 2012), some of which have been worked on a small scale. However, under current market conditions, most of these deposits are not large enough to warrant development on their own. Packaging several nearby pegmatites together could improve the potential for their development. Using an inexpensive semi-mobile primary plant that could be moved from site to site, with a central upgrading plant for cleaning the rough concentrates, could make these individually sub-economic deposits collectively viable.

Another significant driver that could swing the pendulum back toward mechanized mining of Ta is the persistently pos-

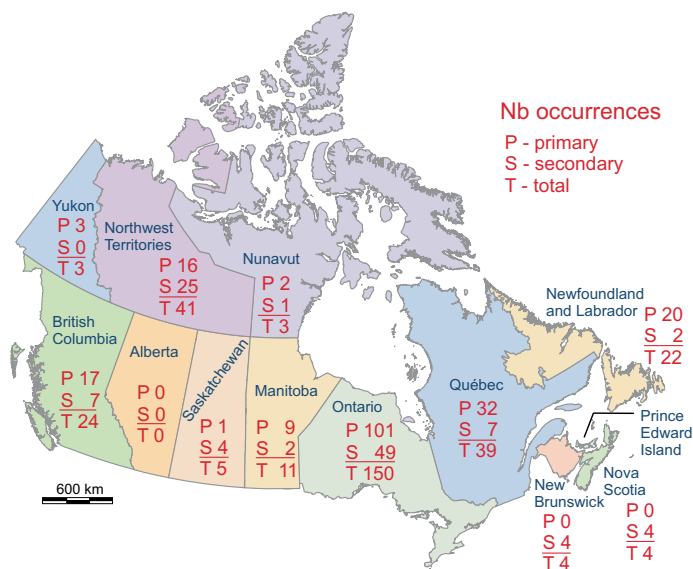




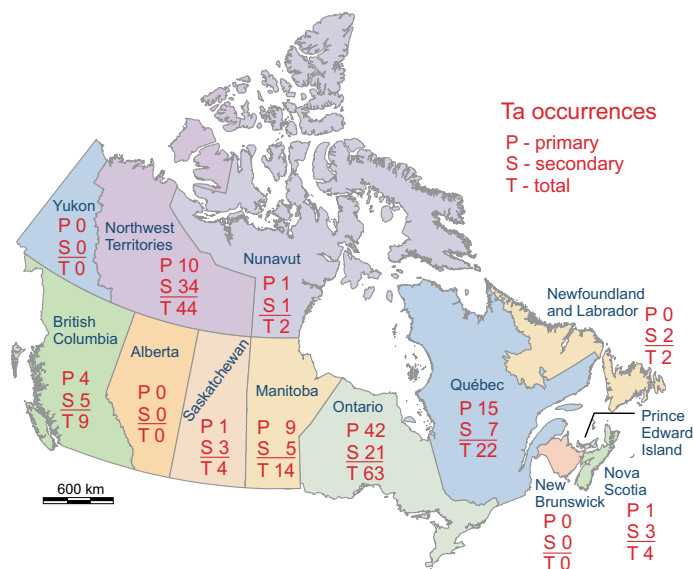
**Figure 11.** Grade and tonnage of a) Nb, and b) Ta deposits associated with carbonatite complexes relative to pegmatites, peralkaline complexes, and rare-element granites. Diagonal lines indicate isotonnage of contained metal oxides. Two deposits plotting along the same isotonnage line will have varying ore grades and tonnages, but will contain the same mass of  $\text{Nb}_2\text{O}_5$  or  $\text{Ta}_2\text{O}_5$ . The highest  $\text{Ta}_2\text{O}_5$  grades correspond to pegmatites. Peralkaline intrusive complexes have the largest resource in terms of contained tonnes of  $\text{Ta}_2\text{O}_5$ . The highest  $\text{Nb}_2\text{O}_5$  grades and ore tonnages correspond to weathering-enriched carbonatite-complex-related deposits followed by hard-rock carbonatite-related deposits. Peralkaline-complex-related deposits also represent significant ore tonnages of contained  $\text{Nb}_2\text{O}_5$ . Relevant references to grade and tonnage sources of information are available in Mackay and Simandl (2014a); with updates from Arrowhead Resources Ltd. projects, Vallieres et al. (2013), Anglo American PLC (2015), and Pittuck et al. (2015) provided in this paper. Abbreviations: (HR) hard-rock ore, (W) weathered ore, (HR+W) hard-rock and weathered ore combined. Modified from Mackay and Simandl (2014a).

itive market fundamentals for lithium raw materials, and the increasing use of Li in batteries (Gruber et al. 2011; Wanger 2011; Perks 2017; Jaskula 2017). Tantalum-bearing zones in pegmatites commonly occur adjacent to and within the same zone as Li mineralization and Ta was historically a co-product of several significant lithium mineral producers, such as Greenbushes in Western Australia and Bikita in Zimbabwe. The increasing demand for Li is a potential catalyst for resur-

recting historic Ta producers and developing new mines in which Ta and Li could be recovered from the same pegmatite body, such as the Wodgina pegmatite, and Mount Marion and Mount Cattlin pegmatites in Western Australia (Tamlin 2017). The Pilgangoora Ta–Li project, Western Australia (Pilbara Minerals Limited), the Mibra Ta mine in Brazil (AMG Company), the Pakeagama project, Ontario, Canada (Tamlin 2017), the Rose Ta–Li project in Québec, Canada (Lavallée 2017), and



**Figure 12.** Distribution of Nb-bearing occurrences in Canada (Simandl et al. 2012). The term ‘primary’ identifies occurrences where Nb is the main substance of economic interest. The term ‘secondary’ refers to occurrences where Nb is listed as potential co-product. The terms carry no implications as to the origin of mineralization.



**Figure 13.** Distribution of Ta-bearing occurrences in Canada (Simandl et al. 2012). The term ‘primary’ identifies occurrences where Ta is the main substance of economic interest. The term ‘secondary’ refers to occurrences where Ta is listed as potential co-product. The terms carry no implications as to the origin of mineralization.

the Separation Rapids pegmatite in Ontario, Canada (Avalon Advanced Materials Inc.), are all examples of potential Ta–Li co-producers.

Historically, the feasibility of Ta extraction from Sn slags was strongly influenced by market conditions (Roethe 1989) and this is still happening today. Only Ta-rich slags can be processed if Ta<sub>2</sub>O<sub>5</sub> prices are low; however, currently sub-economic Sn slag stockpiles that contain Ta may provide a buffer should Ta shortages materialize.

In the long term, potential REE extraction from large, peralkaline-intrusion-related deposits may yield Nb and Ta as by-products of REE extraction. Examples include deposits such as Nechalacho and Strange Lake in Canada (Ciuculescu et al. 2013; Gowans et al. 2017) and the Motzfeldt Sø (Ta–Nb–REE–Zr–U) deposit in Greenland (Tukiainen 1988). However, in most of these cases, unconventional or currently commercially unproven processing technology is required. Furthermore, as in the case of carbonatite-related deposits, the Ta<sub>2</sub>O<sub>5</sub>/(Ta<sub>2</sub>O<sub>5</sub> + Nb<sub>2</sub>O<sub>5</sub>) ratios of concentrates from such deposits will determine their Ta potential.

### New Exploration Methods and Other Developments

It is expected that new deposits will be discovered as exploration methods for Nb and Ta are optimized. Some recent and significant breakthroughs include customizing and optimizing the use of portable X-Ray Fluorescence to provide sufficiently accurate and precise chemical analyses for specialty metals directly in the field (Simandl et al. 2014), optimization of indicator mineral-based exploration methodology to detect Nb–Ta mineralization (e.g. Mackay and Simandl 2015; Mackay et al. 2016), and the use of exploration biogeochemistry (Fajber et al. 2015). Test sites used to improve these methods were located in the Canadian Cordillera and included the Aley carbon-

atite (83.8 million tonnes of proven and probable reserve at 0.50% Nb<sub>2</sub>O<sub>5</sub>; Jones et al. 2014) and the Upper Fir carbonatite (indicated resources of 48.4 million tonnes grading 197 ppm Ta<sub>2</sub>O<sub>5</sub> and 1,610 ppm Nb<sub>2</sub>O<sub>5</sub> and inferred resources of 5.4 million tonnes grading 191 ppm Ta<sub>2</sub>O<sub>5</sub> and 1,760 ppm Nb<sub>2</sub>O<sub>5</sub>; Kulla and Hardy 2015). The Aley deposit was detectable using indicator minerals in stream sediments more than 11 km downstream from the deposit (Mackay and Simandl 2014b; Mackay et al. 2016). The Upper Fir carbonatite was used to test a biogeochemical exploration approach. The results suggest that twigs and needles of fir and spruce are acceptable sampling media and that La, Ce, Pr, Nd, Sm, Dy, Fe, Nb, Ta, P, and Y are promising pathfinder elements. Ashing of twigs concentrated all pathfinders above the lower limit of detection of a commercial analytical procedure involving HNO<sub>3</sub> digestion followed by ICP-MS/ICP-AES analysis (Fajber et al. 2015). A comprehensive review of modern geophysical techniques (with emphasis on gravity, magnetic, and radiometric methods) used in exploration for intrusion-related rare metal deposits, including those containing Ta and Nb, is provided by Thomas et al. (2016). This review demonstrates the utility of such methods in delineating intrusions hosting rare metals, in modelling their third dimension, and in helping to better focus on mineralization. This is achieved using predominantly Canadian examples such as the Oka carbonatite complex, the Tanco pegmatite, and the Nechalacho and Strange Lake peralkaline intrusions.

Current and future effects of recycling in the Ta supply chain are hard to quantify due to ongoing shifts in uses of Ta. Overall, the recycling of Ta scrap generated during the manufacturing process has increased since the 1970’s (Nassar 2017). According to the same study, the overall end-of-life recycling rate of Ta declined from the 22–25% range in the 1990’s to

18% today. This decline coincides with the shift in use of Ta from carbides to sputtering targets, chemicals, and capacitors. The latter are not being recycled at their end-of-life in significant quantities (Nassar 2017). Furthermore, the potential for recovering Ta from end-of-life electronics varies from product to product (Ueberschaar et al. 2017).

## SUMMARY AND CONCLUSIONS

Carbonatite-related deposits supplying concentrates dominated by pyrochlore are currently the main source of Nb in the form of ferroniobium. Deposits related to pegmatites of the rare-element class, belonging to the LCT (lithium–cesium–tantalum) family, are the main sources of primary Ta concentrates, which consist predominantly of columbite–tantalite group minerals. The situation is unlikely to change within the next 5 to 10 years.

The mineralogy of the ore is extremely important in ranking of projects according to their development potential. It controls at least in part the  $Ta_2O_5/(Ta_2O_5 + Nb_2O_5)$  ratio of the concentrate, and indirectly constrains processing options. The higher the  $Ta_2O_5/(Ta_2O_5 + Nb_2O_5)$  ratio is, the better the chance that  $Ta_2O_5$  can be economically recovered.

Major Nb-producing mines are mechanized with relatively well-established resources and reserves. Approximately 90% of Nb (in the form of ferroniobium) currently originates from Brazil, with the majority of that coming from just one mine; therefore, Nb is classified as a ‘critical metal’.

Most of the primary Ta raw materials are currently derived from the historically politically unstable Great Lakes Region of Central Africa, largely from artisanal mines without resource estimates prepared under a certification system. These are the main reasons why Ta is considered to be a critical material, with a significant risk of supply disruption.

Tantalum coexists with Li in several pegmatite deposits in Australia, North America, and South America. The demand for Li minerals is growing rapidly, triggering efforts for reactivating several historic mines and developing new mechanized mines with known Li and Ta resources. If these efforts are successful, the risk of future Ta supply disruptions could be significantly reduced. It is too early to predict to what extent this trend towards Li–Ta coproduction will affect the current Ta supply chain.

Significant Nb and Ta resources are also identified within several known peralkaline-intrusion-related REE deposits; however, in the short- and medium-term, these resources are unlikely to be developed and significantly impact Ta and Nb markets.

From a technical-economic standpoint, the risk of future shortages of Nb and Ta raw materials is minimal, despite their designation as critical minerals. Market elasticity is expected to absorb the long-term reduction in ore grades and depletion of Ta and Nb resources in weathered crusts by allowing for corresponding increased costs of production. Continued improvement of exploration methods targeting Ta and Nb deposits, in combination with possible recovery of Ta and Nb as co-products of REE, Sn, and Li, will reduce this risk even further.

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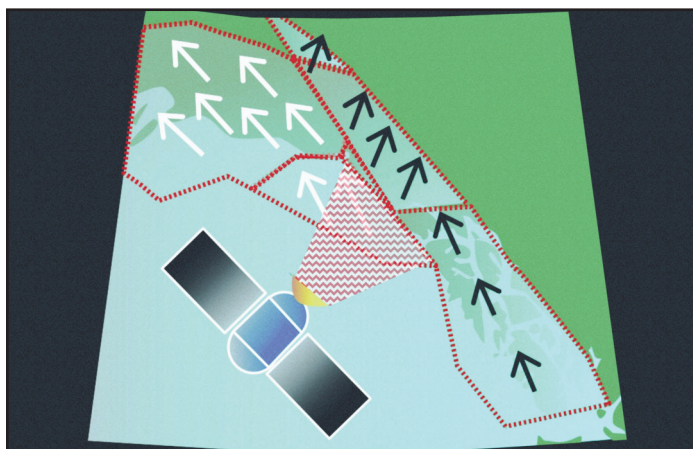
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# REPORT



## EON-ROSE\* and the Canadian Cordillera Array – Building Bridges to Span Earth System Science in Canada

\*Earth-System Observing Network - Réseau d'Observation du Système terrestreE

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“The significant problems we face cannot be solved at the same level of thinking we were at when we created them” (Albert Einstein, New York Times 1946).

## SUMMARY

EON-ROSE (Earth-System Observing Network - Réseau d’Observation du Système terrestreE) is a new initiative for a pan-Canadian research collaboration to holistically examine Earth systems from the ionosphere into the core. The Canadian Cordillera Array (CC Array) is the pilot phase, and will extend across the Cordillera from the Beaufort Sea to the U.S. border. The vision for EON-ROSE is to install a network of telemetered observatories to monitor solid Earth, environmental and atmospheric processes. EON-ROSE is an inclusive, combined effort of Canadian universities, federal, provincial and territorial government agencies, industry, and international collaborators. Brainstorming sessions and several workshops have been held since May 2016. The first station will be installed at Kluane Lake Research Station in southwestern Yukon during the summer of 2018. The purpose of this report is to provide a framework for continued discussion and development.

## RÉSUMÉ

EON-ROSE (Earth-System Observing Network - Réseau d’Observation du Système terrestreE) est une nouvelle initiative de collaboration de recherche pancanadienne visant à étudier de manière holistique les systèmes terrestres, depuis l’ionosphère jusqu’au noyau. Le Réseau canadien de la cordillère (CC Array) en est la phase pilote, laquelle couvrira toute la Cordillère, de la mer de Beaufort jusqu’à la frontière étasunienne. L’objectif d’EON-ROSE est d’installer un réseau d’observatoires télémétriques pour suivre en continu les processus terrestres, environnementaux et atmosphériques. EON-ROSE est un effort combiné et inclusif des universités canadiennes, des organismes gouvernementaux fédéraux, provinciaux et territoriaux, de l’industrie et de collaborateurs internationaux. Des séances de remue-ménages et plusieurs ateliers ont été tenus depuis mai 2016. La première station sera installée à la station de recherche du lac Kluane, dans le sud-ouest du Yukon, au cours de l’été 2018. Le but du présent rapport est de fournir un cadre de discussion et de développement continu.

*Traduit par le Traducteur*

## INTRODUCTION

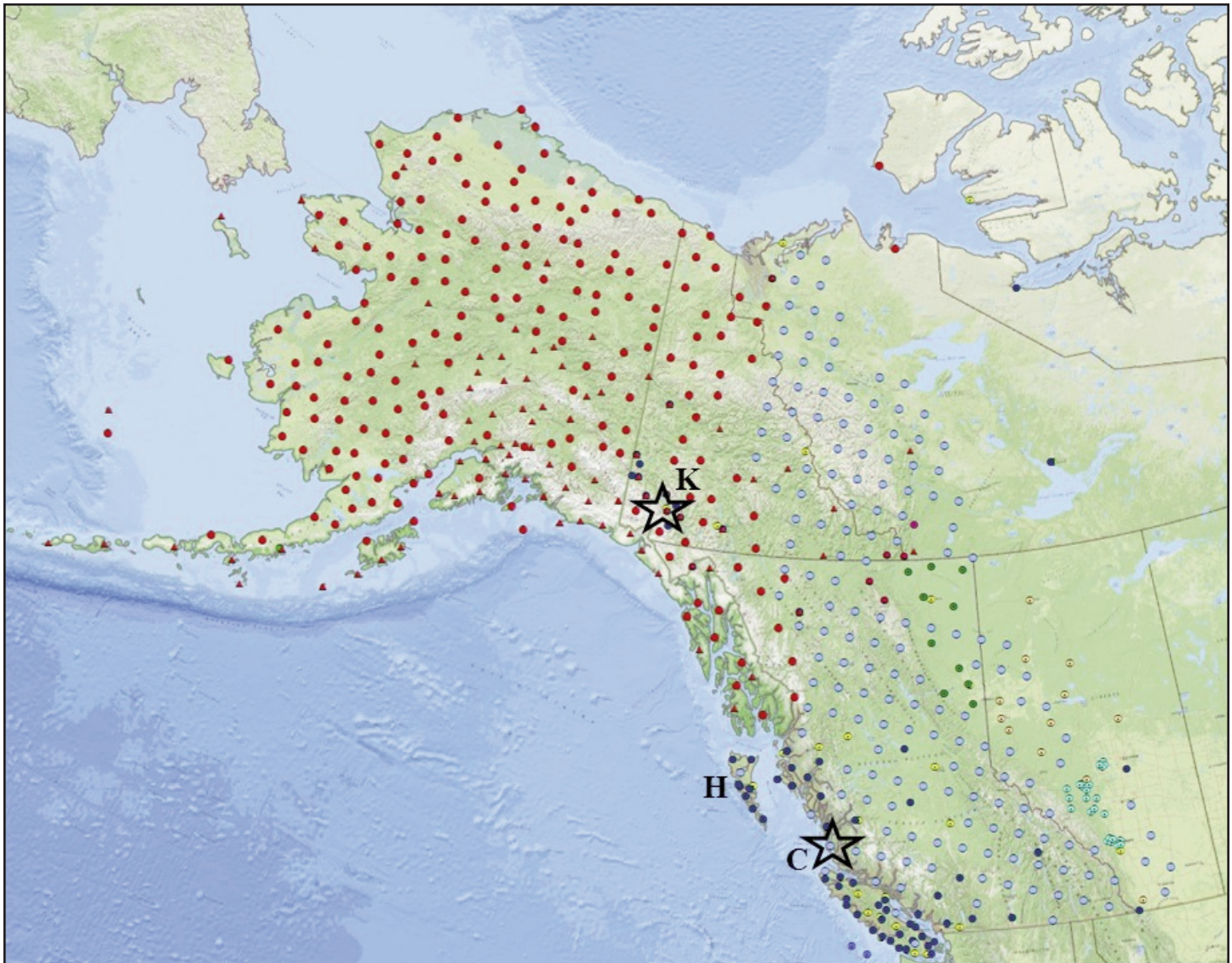
The purpose of this article is to engage and inform the Canadian geoscience community about the exciting opportunities represented by EON-ROSE (Earth-System Observing Network - Réseau d’Observation du Système terrestreE), a proposed new initiative to develop a pan-Canadian research collaboration capable of holistically examining Earth systems from the ionosphere through the Earth’s surface and into the core. The fundamental component is a uniformly-spaced grid of observation stations, successively covering different areas of Canada. The initial component is the proposed Canadian

Cordillera Array (CC Array), spanning the Cordillera of western Canada from the Beaufort Sea to the United States border. The CC Array will build upon the unprecedented opportunities for technical, methodological, and scientific knowledge transfer presented by the coming completion of the US EarthScope program ([www.earthscope.org](http://www.earthscope.org)), which currently has a grid of several hundred telemetered seismic, Global Navigational Satellite System (GNSS) and associated instruments across Alaska and northwestern Canada. The resulting scientific advances in studies of the solid Earth structure, dynamics and hazards enabled by such large-scale integrative networks of geophysical and other scientific instruments provide a strong foundation for driving innovative Earth science. EON-ROSE and the CC Array offer much potential for new breakthroughs in scientific research.

EON-ROSE proposes to formally explore and pursue linkages between solid Earth, surface and atmospheric processes. Although the EON-ROSE initiative came from the solid Earth geoscience community, such a network would be a unique opportunity for many other disciplines, and it has broadened to a truly multidisciplinary effort. It is envisioned as a combined effort of Canadian universities, federal and provincial government agencies, industry, and international collaborators (including those involved in the US EarthScope program and German Helmholtz Association). The US EarthScope program has been very successful but focused on mainly seismic, infrasound GNSS, and magnetotelluric instrumentation.

Here, we propose that progress in understanding complex changes in Earth’s energy budget, the carbon cycle, the water cycle, and human influence within these systems requires consideration of global processes from the ionosphere and atmosphere, through the Earth’s lithosphere, and deep into the mantle. Such an effort requires novel data collection and analysis approaches that would be greatly enhanced by multidisciplinary collaborative research networks bridging Earth System Science. In the spirit of the exceptionally successful Canadian multidisciplinary geoscience Lithoprobe program (1984–2005; e.g. Clowes 2010) the EON-ROSE program will include a wide range of associated and collaborative geoscience research. One key objective is to examine connections between surface geology and the deep structures and dynamics of the crust and upper mantle.

The vision of EON-ROSE is to expand upon the scientific momentum in North America gained from the Lithoprobe and EarthScope research and data collection initiatives. The specific vision for the CC Array is to install a network of mainly telemetered observatories (Fig. 1), each equipped with a suite of sensors such as broadband seismometers (including ocean bottom seismometers in the Beaufort Sea and the eastern Pacific Ocean), GNSS equipment, meteorological sensors, permafrost monitors, atmospheric gas sensors, shallow borehole temperature and moisture sensors, riometers (to monitor the electromagnetic-wave ionospheric absorption in the atmosphere), and magnetometers. Many of the stations will be in place temporarily for up to three years (longer for the GNSS



**Figure 1.** Proposed distribution of Earth observation stations for the Canadian Cordillera Array (CC Array) at an 85 km spacing. The red circles and triangles are current distribution of the 193 Transportable Array (TA) and 87 cooperative seismic, meteorological, and infrasound US TA stations in Alaska and northwestern Canada. The light blue circles are the ~ 165 proposed Earth observation stations for the CC Array. The various other colours and symbols are broadband seismometers from a variety of academic and federal government groups (courtesy of S. Azeveda and R. Busby). K – Kluane Lake Research Station, C – Calvert Island, H – Haida Gwaii Islands.

equipment), but the intention is to leave some stations in place for long-term Earth and environmental monitoring and science research across Canada. Although the initial network is proposed to be on an approximately uniformly-spaced grid, it is expected that there will be more detailed follow-up in areas of special interest with more closely spaced station distributions (as with the EarthScope Flexible Array), coupled with seismic and other geophysical surveys (as with Lithoprobe), and on-ground geological surveys and studies.

**Benefits of Multiple Sensors at Each Station**

Recent scientific and technical advances of the EarthScope program and its associated integrative instrumentation developments and science goals (e.g. Aster and Simons 2015) provide a strong foundation for developing the methodology for EON-ROSE and CC Array. Many modern geophysical instru-

ments make measurements that benefit multiple fields of research, allowing a multidisciplinary approach to observation networks and the exploration of cross-disciplinary scientific problems. Examples from EarthScope support the power of combining several sensors in one station.

Infrasound signals (i.e. low-frequency sound undetectable by humans) were detected by the EarthScope seismic and infrasonic sensors (e.g. de Groot-Hedlin et al. 2008, 2011; Hedlin et al. 2010; Walker et al. 2011). These infrasound signals can be used to study wind and temperature structure in the atmosphere. When the US Transportable Array (TA) was located in the ‘tornado alley’ of the US Midwest, dedicated infrasound sensors were added to exploit this potential for research. Using Delauney triangulation (a computational technique that created a triangular grid pattern with the TA stations such that no station was isolated by itself in one of the trian-

gles), de Groot-Hedlin et al. (2014) developed the capacity to track the motion of atmospheric gravity waves across the TA from slow-moving, long-period pressure pulses. Weather-related gravity waves describe the disturbance of fluids (or gases) from an equilibrium state. Propagating gravity waves can develop from the outward moving wind gusts at the leading edge of thunderstorms (Miller 1999; Knupp 2006). Gravity waves are of interest to numerical weather modellers and atmospheric scientists because they play a vital role in the transfer of energy and momentum between atmospheric layers and in global-scale circulation patterns (Holton et al. 1995). The TA sensors have also been used to study outward moving wind gusts at the leading edge of thunderstorms (Tytell et al. 2016). It remains of interest to determine how these sensors could improve modelling of weather processes in an operational setting and improve forecasting.

Another example that illustrates the benefits of co-locating sensors occurred recently in Nevada and California (Smith et al. 2016a). The co-location of seismometers and cameras offered real-time support to situational awareness for first responders monitoring wildland and interface fires. Due to the vast and remote nature of Canadian territory at risk from wildfires, this could be of great value in the early detection and real-time analysis of wildfires.

### **Integration of Solid Earth Geosciences with Space Weather, Numerical Weather Modeling, Critical Zone Science and Climate Change Research**

A key objective of the proposed EON-ROSE and CC Array initiatives is to integrate solid Earth geoscience research with space weather observations, numerical weather modelling, critical zone science and climate change research.

*Space weather* refers to the changes caused by energetic particles and fluctuating magnetic fields above the thermosphere, which is the uppermost layer of the atmosphere that can be considered a continuous gas. The thermosphere is located above the stratosphere and is about 100 km above the troposphere, where day-to-day weather occurs. The Sun regularly emits giant clouds of ionized gas with  $10^{16}$  g or more of hot plasma per event, causing geomagnetic storms that form the aurora and can severely disturb communications systems (Lanzerotti 2001), disrupt electric power grids (Boteler 2001), as well as cause significant damage to Earth-orbiting spacecraft.

*Numerical weather modelling* enables forecasts that account for dynamic, thermodynamic, radiative, and chemical processes working on temporal and spatial scales from seconds to weeks and hundreds of metres to thousands of kilometres (Bauer et al. 2015; Brunet et al. 2015). Recent experiences with extreme weather events such as Hurricanes Harvey, Irma and Maria have demonstrated the continued critical need for accurate numerical weather prediction. Although technological and scientific advances have permitted accurate global weather forecasting capabilities to extend by about one day per decade, there remain several challenges including obtaining physically consistent initial conditions by observations, and in better evaluating the accuracy of forecasts through ensemble predictions,

i.e. sensitivity modelling exercises in which initial parameters are varied (Bauer et al. 2015; Brunet et al. 2015).

The *critical zone* (e.g. as defined by the US National Research Council in 2001) forms the complex region that is essential for supporting life, i.e. from the top of the forest canopy through the soil to the bottom of the deepest weathering and the base of aquifers (Wymore et al. 2017). Critical zone science includes investigation of crucial societal issues, such as access to potable drinking water, the impact of climate variability on soil development, the evolution and sustainability of soils and soil biomes, carbon sequestration in the near-surface and landslide studies (Goddéris and Brantley 2013).

*Climate change* and related issues such as population growth, increased vulnerability, and opportunities to increase resilience, to natural hazards, and the need for long-term sustainability of resources (including minerals, energy, water and food) demand new approaches to integrated Earth System Science (e.g. Zoback 2001). Many aspects of the response to these challenges hinge on progress in Earth System Science, which will be aided by the multidisciplinary approach to Earth monitoring embodied by the EON-ROSE concept.

### **Call for Collaboration**

This report presents an overview of our vision for EON-ROSE (Table 1) including a discussion of the potential application of this proposed holistic interdisciplinary approach to the development of exploration models for mineral deposits. It also includes a summary of ‘white papers’ (listed in Table 2) that were presented at a series of recent developmental workshops. These documents are essentially scoping studies that outline proposals for specific areas or scientific themes that could be investigated as part of the proposed project. Table 2 contains a listing of white papers prepared as part of this process, and we refer to these specifically in the last part of the paper. They are not listed in the references that conclude the paper.

Many of these white papers are available from a website set up as part of the CC Array initiative ([www.ccarrray.org](http://www.ccarrray.org)). The purpose of this report is to provide a framework for continued discussion and development of this proposed national initiative. Interested readers are welcome to contact any of the authors, other authors of white papers, workshop participants (Table 3), or other people mentioned in the organizational chart on the CC Array website.

### **EON-ROSE AND CANADIAN CORDILLERA ARRAY CONCEPT INITIATION**

The EON-ROSE concept arose from discussions at the 2015 EarthScope workshop related to potential new initiatives to follow the planned completion of the decadal-scale US EarthScope program by September 2020. Although the final phase of EarthScope has now placed instruments across Alaska and parts of northwestern Canada, there were no formal plans in Canada to start an ‘EarthScope-like’ program prior to 2015. The idea was first presented at the October 2015 annual Council of Canadian Chairs of Earth Science Departments meeting in Ottawa. Subsequent consultations resulted in letters of sup-

**Table 1.** Timeline for EON-ROSE\* Project and the Canadian Cordillera Array (CC Array)

Date	Event	Advances
February 2013	Meeting to develop 'BC Array' at PGC	TA Array stations placed in NW Canada
June 2015	EarthScope Workshop	Idea emerged to bring EarthScope-like program to Canada
October 2015	First CCCESD Presentation	First white papers developed at McGill University
March 2016	NGSC Presentation	Start of buy-in from Geological Survey of Canada (GSC)
May 2016	CGU/CMOS Presentation	Start building community
May 2016	GAC-MAC Workshop	Continue building community
August 2016	SGT Forum Presentation and Poster	Reach out to US community
August 2016	Calgary and Ottawa brainstorming workshops	CC Array separated out as pilot project
October 2016	Second CCCESD Presentation	Report on brainstorming workshops
November 2016	Planning Meeting	Dave Eaton agreed to be Director; developed organization chart
December 2016	GeoPRISMS-sponsored Workshop at American Geophysical Union	Need for letter of interest to IRIS and UNAVCO (delivered in January); Expanding community to Critical Zone Science (CZS) and Space Physics
December 2016	Meeting with Director General of Geological Survey of Canada after EarthScope Townhall	Expand GSC support and interest
February 2017	Cordilleran Tectonics Workshop	Met with Hakai Institute
March 2017	GNSS – Focused Workshop	Proposed draft for GNSS receiver deployment; Building connections with CZS and Space Physics
March 2017	SWARM Conference	
April 2017	First CC Array Townhall	Report on NSERC SPGN LOI submission; present website
May 2017	CC Array Workshop at EarthScope 2107 Workshop	Establish connections with NSF Program Officers; Connect with the Chinese SinoProbe program
June 2017	CC Array Planning Meeting and Session at GSA Rocky Mountain Section Meeting	Developed first draft of proposed critical zone stations for CC Array
August 2017	CC Array Scientific and Planning Meeting	Report on first station installation spring 2018; Developed first draft of proposed distribution of weather stations for CC Array; Final report to be start of scientific strategic plan

\*EON-ROSE - Earth-System Observing Network - Réseau d'Observation du Système terrestrE  
 BC Array - British Columbia Array (now combined with Yukon as CC Array), CC Array - Canadian Cordillera Array  
 CCCESD - Canadian Council of Chairs of Earth Science Departments, CGU - Canadian Geophysical Union, CMOS - Canadian Meteorological and Oceanographic Society  
 GNSS - Global Navigational Satellite System, IRIS - handles seismic data for EarthScope and other North American groups, NGSC - National Geological Surveys of Canada  
 NSERC SPGN LOI - National Science and Engineering Research Council of Canada Strategic Partnership Grants Letter of Intent, NSF - US National Science Foundation  
 SWARM - European Space Agency satellite mission to measure Earth's magnetic field, SGT - Structural Geology and Tectonics  
 TA - transportable array, UNAVCO handles the GPS data from the Plate Boundary Observatory of EarthScope

port for the concept from the Yukon Geological Survey, Repsol, Nanometrics Inc., and Environment and Climate Change Canada. The first white papers outlining research opportunities under a future EON-ROSE program were coordinated by Christie Rowe at McGill (Amos et al.; Liu et al.; see Table 2).

All of the white papers were first summarized at information sessions at the Canadian Geophysical Union/Canadian Meteorological and Oceanographic Society (CGU/CMOS) meeting (Fredericton, May 29, 2016) and the GAC-MAC meeting (Whitehorse, May 31, 2016), with further calls for interest to these communities. Subsequently, two brainstorming workshops were held at Mount Royal University in Calgary (August 17–19, 2016) and at the University of Ottawa (August 21–23, 2016; participants listed in Table 3). One major theme that

emerged from these first workshops was the need to broaden the research community engaged in EON-ROSE; these efforts resulted in a workshop sponsored by GeoPRISMS (Geodynamic Processes at Rifting and Subducting Margins; www.geoprism.org) at the Fall 2016 AGU meeting. A subsequent section will summarize the key points of these white papers (see Table 2 for further information about the white paper authors and subject material).

**SEPARATION OF THE CANADIAN CORDILLERA ARRAY FROM THE EON-ROSE UMBRELLA AS A PILOT PROJECT**

A significant outcome from the Ottawa workshop in August 2016 was a proposal to separate the Canadian Cordillera Array (CC Array) from the wider umbrella of EON-ROSE in order

**Table 2.** White papers submitted for the EON-ROSE\* brainstorming workshops. These documents are not included within the reference list, but can be obtained from the Canadian Cordillera Array website ([www.ccarrray.org](http://www.ccarrray.org)) or from the authors.

Authors	Topic
Amos, Harrington, Kirkpatrick, Leonard, Levson, Liu, Morell, Regalla, Rowe	Active faults of the Cascadia forearc: Implications for seismic hazard and tectonic evolution
Barnes	Canadian Environmental Change Research Network (CECRN): analysis and mitigation of global change and major natural hazards
Brunet	NEWP – Numerical Environmental and Weather Prediction
Colpron	Nature of the crust in North Yukon?
Elliott	Strain distribution across eastern Alaska and western Canada
Frederiksen, Eaton, Morozov	The Trans-Hudson Underlying Mantle Project (THUMP): a proposed teleseismic project for EarthsCAN
Freymueller	Distributed plate boundary deformation in the Northern Cordillera
Godin	Faults, tectonic inheritance, fluids, and seismicity: Towards an integrated Canadian Fault Atlas
Hyndman, Schaeffer, Audet, Aster, Schutt, Schmidt	Consequences of margin plate interactions in the Canadian Cordillera: BC Array concept
Kushner	Community Geoscience projects
Liu, Harrington, Darbyshire	Structure, seismicity and earthquake triggering in the St-Lawrence rift system
McCormack, Adams	Monitoring natural phenomena
Miller, Else, Sastri, Williams, Papakyriakou, Melling	CO <sub>2</sub> Fluxes and transformations in the Arctic marine system: A node in the Global Carbon Cycle
Molnar	Transportable seismic arrays for ambient noise tomography imaging: Toward physics-based wave propagation modeling of earthquake scenarios
Myers	Towards integrated ocean observing systems, with the Atlantic as an evolving example
Ndimovic, Audet, Bostock, Calvert, Darbyshire, Dosso, Frederiksen, Liu, Liu, Welford	National facility for seismic imaging
Risk	Gas mapping as a geospatial resource for collaborative science
Scherwath, Dewey, Pirenne, Moran, Heesemen	Ocean Networks Canada and its role in Earth observing systems
Snyder	Semi-permanent stations for multi-azimuthal teleseismic studies of anisotropy and structure
Stevenson	Geological maps as historical documents
Stevenson, Darbyshire, Rizo, de Souza	Mapping the lithospheric mantle
Unsworth, Ferguson, Jones, Craven and Farquharson	Magnetotelluric imaging of the Canadian lithosphere: A historical perspective and future opportunities in EarthsCAN

\*EON-ROSE - Earth-System Observing Network - Réseau d'Observation du Système terrestreE

to move forward more quickly and take advantage of the time-limited opportunities presented by the EarthScope US Array Transportable Array (TA) instruments currently located in Alaska and northwestern Canada (Fig. 1). Timing is crucial for deployment of the CC Array because these EarthScope TA instruments will be removed in the summers of 2019 and 2020 and installing new stations in isolated regions such as eastern Alaska and northwestern Canada is logistically challenging. To take advantage of the trained EarthScope installation teams and expertise and the investment in permitting and installation expertise already funded by the US National Science Foundation, the CC Array must move forward on a faster timeline than the nationwide EON-ROSE initiative. The general consensus was that combining the proposed Yukon array (white

paper by Colpron; Table 2) and British Columbia array (white paper by Hyndman et al.; Table 2) as the CC Array would make a good proof of concept for EON-ROSE and provide an effective stepping stone to a successful national program. It is important to keep the pan-Canadian goal of EON-ROSE in the forefront of planning and strategic thinking, and to build the national initiative on a time schedule that would allow the full EON-ROSE instrumental network to roll out across Canada in an efficient manner.

### SUMMARY OF WHITE PAPERS

After the initial two white papers, more detailed white papers were submitted for the information sessions and the brainstorming workshops (Table 2). Of these white papers, 14 are

**Table 3.** List of participants at the Calgary and Ottawa EON-ROSE\* brainstorming workshops.

Position	Affiliation	Name
<b>Calgary Workshop</b>		
<b>Coordinator</b>	Mount Royal University	Boggs, Katherine
<b>Presenter</b>	Geological Survey of Canada / University of Victoria	Hydman, Roy
	Ocean Networks Canada, University of Victoria	Scherwath, Martin
<b>Participant</b>	Purdue University	Elliott, Julie
	Repsol Inc.	Hsieh, Jean
	University Alaska Fairbanks, DENO	Freymueller, Jeff
	University of British Columbia	Clowes, Ron
	University of Saskatchewan	Llewelyn, Ted
	University of Toronto	Kushner, Paul
	University of Victoria	Morell, Kristin
	Yukon Geological Survey	Colpron, Maurice
	Alberta Geological Survey	Schultz, Ryan
	Association of Professional Geoscientists of Alberta	Sneddon, Tom
	Carbon Management Canada Research Institute	Osadetz, Kirk
	Mount Royal University	Droboth, Jason <sup>#</sup>
		Fornwald, Connor <sup>#</sup>
		Gopal, Saha
		Witvoet, Leela <sup>#</sup>
	Simon Fraser University	Calvert, Andy
	University of Calgary	Bao, Xuewei <sup>#</sup>
		Dettmer, Jan
		DiCaprio, Lydia
		Eaton, Dave
	Else, Brent	
	Ferguson, Ron	
	Gilbert, Hersh	
	Lauer, Rachel	
	Weir, Ron <sup>#</sup>	
	Leth, Maria <sup>#</sup>	
	Leonard, Lucinda	
	Nissen, Edwin	
	Relf, Carolyn	
<b>Ottawa Workshop</b>		
<b>Coordinator</b>	Mount Royal University	Boggs, Katherine
<b>Presenter</b>	University of Ottawa	Audet, Pascal
	Canadian Geodetic Survey	Klatt, Calvin
	Canadian Hazards Information Services	Adams, John
	Geological Survey of Canada	Snyder, David
	Geological Survey of Canada / University of Victoria	Wang, Kelin
	McGill University	Liu, Yajing
	Nanometrics Inc.	Spriggs, Neil
	Oxford University	Sigloch, Karin
	Queens University	Godin, Laurent
	St Francis Xavier University	Baillie, Jennifer
	University of British Columbia	Clowes, Ron
	University of Ottawa	Schaeffer, Andrew
	Université du Québec à Montréal	Stevenson, Ross
	University of Toronto	Kushner, Paul
	University of Victoria	Barnes, Chris
	<b>Participant</b>	Western University
Canadian Geodetic Survey		Craymer, Mike
Geological Survey of Canada		Ackerley, Nick
University of Ottawa		Montsion, Rebecca <sup>#</sup>
Université du Québec à Montréal		Darbyshire, Fiona
		Pinti, Daniele
	University of Toronto	Murray-Bergquist, Louisa <sup>#</sup>

<sup>#</sup> = student participants

DENO - Director of the EarthScope National Office; \*EON-ROSE - Earth-System Observing Network - Réseau d'Observation du Système terrestreE

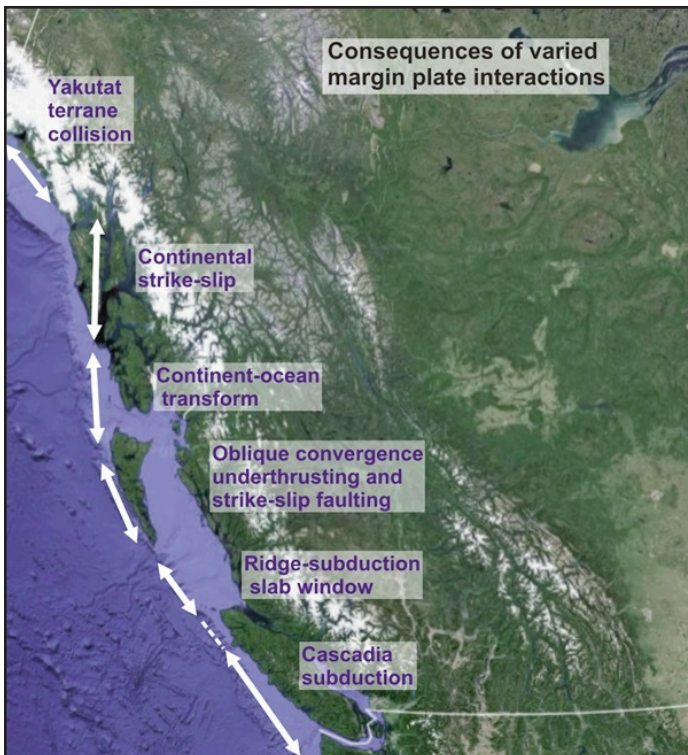


Figure 2. Tectonic characteristics off the west coast of Canada.

related to solid Earth geosciences, 3 to oceanography, 2 to atmospheric gases, 1 to climate change and 1 to weather modelling. This indicates that the solid Earth geosciences are presently over-represented, due in part to the background and expertise of the proponents and because the Canadian geoscience community is familiar with the successes of the Litho-probe and EarthScope programs. Ongoing efforts to build a truly multidisciplinary EON-ROSE initiative and research community will focus on expanding the role of studies outside solid Earth geoscience, to hopefully make the whole greater than all the individual parts. The proposals contained in the white papers can be grouped in part on the basis of geography, but some proposals are of a more thematic nature.

### CC Array – Western Canada with Adjoining Arctic Canada

Several white papers focused on western Canada (Amos et al., Colpron, Elliott, Freymueller, Hyndman et al., Miller et al., Nedimović et al., and Scherwath et al.; see Table 2) and outlined the need for the CC Array. Colpron pointed out that the US Array stations only cover the western half of the “Yukon Stable Block” (YSB; located in north central Yukon Territory). The YSB has some interesting and enigmatic features, such as the underlying Paleoproterozoic Wernecke Group, which is only found in this region of the Northern Cordillera, and Cretaceous and Cenozoic structures that are deflected around the YSB. The white paper by Hyndman et al. (see Table 2) describing the proposed BC Array emphasized the need to better understand the plate structure and seismicity of the complex tectonic setting off the west coast of British Columbia, which includes normal subduction, slab windows, ridge triple junc-

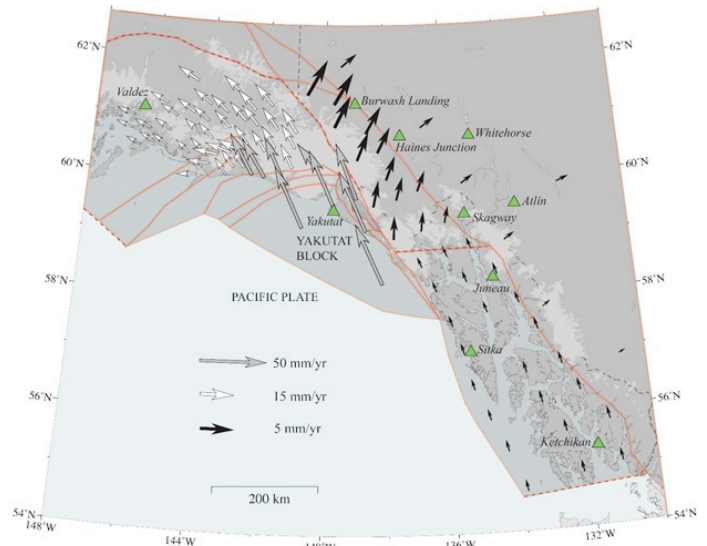


Figure 3. Global Navigational Satellite System (GNSS) - derived model predictions of block motions (relative to stable North America) in southeastern Alaska and western Canada. Red lines show boundaries between blocks; dashed lines indicate uncertain boundaries. Model from Elliott et al. (2016). More information about the model blocks and data used can be found in Elliott et al. (2010; 2013).

tions, possible incipient subduction, transform faulting, and terrane collision (Fig. 2). GNSS data, seismicity and modelling (Elliott et al. 2010, 2013, 2016) show that deformation along this active margin is spread over a broad region. Haida Gwaii (off the west coast in northwestern BC) and the adjacent mainland coastal areas appear to be moving towards the north (Mazzotti et al. 2003). Further north, the Yakutat Block is colliding with southern Alaska, resulting in  $\sim 3$  cm/year of convergence that is accommodated over  $\sim 100$  km (Elliott et al. 2010, 2013, 2016; Fig. 3). This oblique collision appears to be transferring strain to the north and northeast, causing active deformation across the Richardson and Mackenzie mountains (Mazzotti and Hyndman 2002; Leonard et al. 2007; Leonard et al. 2008). One intriguing question is to what extent the strain transfer occurs diffusely across hundreds of kilometres, as opposed to being accommodated by rigid blocks and a few discrete faults. Although a portion of this active margin was covered by the EarthScope US Array stations, the distribution of continuous GNSS sites is extremely sparse. A well-distributed seismic and continuous GNSS network is necessary for measuring the active tectonics. The GNSS network is also needed to measure the deformation associated with glacial isostatic adjustment and would also be beneficial for assessing environmental parameters such as hydrological cycle loading (Rocken et al. 1993, 1995; Bevis et al. 1994), soil moisture (Larson et al. 2005; 2008; Larson and Small 2013) and snow depth (Larson and Nievinski 2012; Larson and Small 2013; McCreight and Small 2014). Signals from glacial isostatic adjustment (e.g. Larsen et al. 2005) and these environmental effects are mixed together in the crustal motions recorded by GNSS, and measurements from complementary terrestrial and satellite sensors are necessary in order to separate them successfully. The EON-ROSE project could provide terrestrial data to complement remote sensing data such as those provided by the



GRACE-FO (Gravity Recovery and Climate Experiment – Follow On) satellite soon to be launched by NASA.

In the area of the CC Array there is a need for studies of recent (neotectonic) fault activity, especially on southern Vancouver Island (Morell et al. 2017) and potentially across much of southwestern British Columbia. For example, using a multidisciplinary approach that incorporates geophysics, LIDAR images and field work, Morell et al. (2017) demonstrated that the Leech River Fault (southern Vancouver Island) experienced at least 3 earthquakes greater than magnitude 6 during the last 15,000 years. Studies of neotectonic activity are rare in Canada compared to the United States due to sparse instrumentation, sparse high-resolution imagery, and a sparse fault database. Canada needs to improve in this regard because these faults do not stop at the international boundary and active fault identification supports local seismic hazard characterization. Studies of neotectonic processes will also be necessary across the Richardson and Mackenzie mountains to understand how strain is so broadly distributed through this region from the collision with the Yakutat Block, as discussed above.

The white papers by Unsworth et al. (on magnetotellurics; see Table 2) and by Risk (on gas mapping for collaborative science; see Table 2) outlined two diverse sensor types for inclusion in the CC Array Earth observation stations. Magnetotelluric (MT) data have proven useful for 3-D studies of potential geothermal prospects in fault zones and volcanic settings in British Columbia, the Yukon and elsewhere (Unsworth et al. white paper). MT has also been used effectively for mineral exploration including porphyry copper (Hubert et al. 2016) and some other types of sulphide deposits (Jones et al. 2014). The white paper by Risk outlines how various gas sensors could also have multiple applications ranging from monitoring volcanic activity (e.g. radon, CO<sub>2</sub>, CH<sub>4</sub>, volatile organic compounds) to environment and health (e.g. oxygen, nitrogen and sulfur oxides, radon) and permafrost thawing and impact of climate change (e.g. CH<sub>4</sub>, CO<sub>2</sub>).

Ground motion visualizations that have emerged from the EarthScope project have made it possible for the first time to develop earthquake wave visualizations fields at continental scales (e.g. <https://www.iris.edu/hq/programs/epo/visualizations>). Natural hazard mitigation and risk assessment in areas where strong ground motions would be expected were significant components of discussions during the brainstorming workshops in both Ottawa and Calgary. In Canada, the Canadian Hazard Information Services (CHIS) monitors and provides information on hazards including earthquakes, volcanoes, tsunamis, landslides and geomagnetic storms. CHIS management proposed possible collaborations ranging from providing archival storage and data dissemination to sharing their expertise on sensors and deployment.

The white paper by Molnar (see Table 2; also Molnar et al. 2014a, b) proposed that earthquake simulation techniques provide one of the best methods for addressing uncertainty for future ground-shaking estimates in order to better evaluate earthquake response and planning. She proposed using an equivalent to the EarthScope Flexible Array to improve the sedimentary velocity model for the Georgia Basin in the Metro

Vancouver area by improving the resolution beyond the current coarse spacing (~ 250 m to 1 km). The possibility of increasing the site density of seismographic, GNSS, and other instrumentation in areas of special interest was also proposed by the Hyndman et al. white paper (Table 2). This approach is similar to that employed for the EarthScope Flexible Array component, as currently deployed across the Mackenzie Mountains (Witt et al. 2017).

### Central Canada

Although the details of EON-ROSE beyond the proposed CC Array have not been established, the white papers by Frederiksen et al. (on the Trans-Hudson Underlying Mantle Project) and by Liu et al. (on the St. Lawrence Rift Valley) proposed some deployment possibilities for future phases of EON-ROSE. Frederiksen et al. proposed filling in a significant gap in broadband seismometers across Saskatchewan and Manitoba to examine the tentative attribution of a local seismic cluster near Esterhazy in southeastern Saskatchewan to dissolution collapse in evaporite deposits. As outlined by Liu et al., the St. Lawrence rift system in eastern North America is the highest seismic hazard region in eastern Canada due to the Lower St. Lawrence, Charlevoix and Western Quebec seismic zones. Seismicity along the St. Lawrence rift system is enigmatic, as the state of stress inferred from earthquake focal mechanism solutions deviates significantly from interpretations based on regional borehole measurements. Although the earthquakes are generally associated with reactivated late Proterozoic Iapetus rift structures, the seismicity appears to scatter around the major rift faults instead of clustering on them. A network of monitoring stations would aid our understanding of this complex region and its seismic hazards.

### Atlantic Canada

One intriguing tectonic target in Atlantic Canada was outlined by Pollock et al. (2015) in their study of Avalonia in southeastern Newfoundland and southern Cape Breton. Their preferred model was for one Late Precambrian arc with significant compositional, tectonic and structural variation along strike. An EarthScope-like array could determine whether this arc formed as a 180° orocline bend similar to the Sunda-Bonda arc (van Staal et al. 1998) or a cognate arc system similar to the Tonga-Kermadec-New Zealand arc system (Pearce et al. 1999).

The most catastrophic tsunami in recorded Canadian history was triggered by a 7.2 magnitude earthquake on the southern edge of the Grand Banks on 18 November, 1929 (Murty 1977; Piper et al. 1988; Evans 2001; Clague et al. 2003). A submarine slope failure in excess of 200 km<sup>3</sup> was triggered, which became a turbidity current that broke all 12 telegraph cables along the continental slope south of Newfoundland (Heezen and Ewing 1952; Fine et al. 2005). Twenty-seven people were killed in Newfoundland and one in Nova Scotia (Cranford 2000; Clague et al. 2003). The possible consequences of another event of this type in the 21<sup>st</sup> century provide an obvious rationale for improved monitoring of seismic activity and other indicators.

The first deployment of the new ocean bottom seismometer facility proposed for EON-ROSE will be in the Atlantic Ocean (white paper by Nedimovic et al.; Table 2). The white paper by Myers (Table 2) described the collaborative approach for the integrated Atlantic Ocean Observatory.

### **Oceanography and Atmospheric Sciences**

Multidisciplinary collaborative opportunities were outlined in white papers by Kushner, Nedimovic et al., Sherwath et al., and Miller et al. (Table 2). The Nedimovic et al. white paper described a Canadian Foundation for Innovation application to fund an ocean bottom seismometer facility that could be available for deployment off the west coast of British Columbia or in the Beaufort Sea as early as 2020, after initial deployment in the Atlantic Ocean. The Sherwath et al. white paper (Table 2) described potential collaborations with Ocean Networks Canada (ONC), including the Neptune and Venus cabled ocean observatories that already collect data on geological, biological, chemical and physical aspects of the oceans and seafloor. The Kushner white paper proposed following the model of the Climate Change and Atmospheric Research program of NSERC and infrastructure collaboration in the area of advanced research computing across the disciplines represented by this initiative.

### **Pacific, Arctic and Atlantic Oceans**

The Arctic Ocean is a precarious net sink of atmospheric CO<sub>2</sub> (white paper by Miller et al.; Table 2). To predict magnitudes and directions of carbon fluxes through the Arctic Ocean, data at much greater temporal and spatial resolutions are required, and the necessary observations are not currently possible with conventional camp- or ship-based chemical oceanography. Presently there is one functioning observatory in Cambridge Bay (operated by ONC) equipped with CO<sub>2</sub> system sensors coupled with an air-sea CO<sub>x</sub> flux tower on a small island offshore in Dease Strait (south of Victoria Island, Nunavut), with plans for a second in southwestern Hudson Bay. The Miller et al. white paper suggested linking efforts from multiple countries to monitor the Arctic Ocean through the EON-ROSE initiative and perhaps using this proposed research network to strengthen collaborative research on the Arctic Ocean. Although the Myers white paper (Table 2) focused on the Atlantic Ocean, the proposed collaborative approach to an Integrated Atlantic Ocean Observing System could also be applied to the Pacific Ocean or the Arctic Ocean.

### **POSSIBLE APPLICATIONS TO MINERAL EXPLORATION**

As with Lithoprobe, we envision that funding will be available to support diverse geoscience studies, such as field-based research, geochemistry, geochronology and other more detailed geophysical studies, such as seismic reflection and refraction experiments. Technological advances from the Lithoprobe program were beneficial for improving images of base-metal deposits (e.g. Sudbury impact structure, Creighton 402 Orebody; Eaton et al. 2010), uranium deposits (e.g. Athabasca Basin, McArthur River Mine; Hajnal et al. 2010), and diamondiferous kimberlites (e.g. Diavik, A154 pipe; Snyder and Grütter 2010). Today, a new frontier is to improve our

understanding of the subcontinental lithospheric mantle (SCLM), which is considered an important source reservoir for diamonds (Shirey et al. 2002; Malkovets et al. 2007), rare earth elements (Smith et al. 2016b) and other metals (Au, Cu, Mo, Pb, Zn; Pettke et al. 2010; Groves and Santosh 2015). Mantle influence and/or sources are suggested for REE deposits hosted by both alkali syenites (Kramm and Kogarko 1994; Stevenson et al. 1997) and carbonatites (Simonetti et al. 1995; Yang et al. 2011; Baatar et al. 2013; Moore et al. 2015). The US EarthScope program (Long et al. 2014) has greatly improved imaging of the SCLM under the US Cordillera (Becker et al. 2014; Refayee et al. 2014; Meqbel et al. 2014; MacCarthy et al. 2014; Lekić and Fischer 2014; Hopper et al. 2014; Porritt et al. 2014), but the Canadian Cordillera lacks the same SCLM resolution.

Recently, Groves and Santosh (2015) emphasized the need to expand traditional exploration models to include common tectonic settings to improve discovery rates for greenfield exploration. Groves and Santosh (2015) specifically referred to recent models for iron oxide-copper-gold (IOCG) deposits, intrusion-related gold systems and Carlin-type gold deposits, all of which suggest common controls by craton margins or suture zones with sub-Moho magma chamber sources. Changing exploration foci to consider lithospheric boundaries could aid in discovering other associated deposit types, such as komatiite-associated Ni-Cu-PGE deposits (Begg et al. 2010; Maier and Groves 2011; Groves and Santosh 2015). A similar exploration model would also be appropriate for giant porphyry-type Cu-Mo-Au deposits such as the Bingham Canyon deposit, as demonstrated using Pb isotopes by Pettke et al. (2010). Such exploration strategies require an integrated multidisciplinary approach among field-based geological, isotopic and geophysical studies; an approach which will be possible through the proposed CC Array program.

### **The Australian PACE Program: An Example of Interdisciplinary Approaches for Mineral Exploration**

The Australian PACE (Plan for Accelerating Exploration) initiative provides several interesting examples that illustrate the positive benefits of interdisciplinary approaches to mineral exploration (Scott and Jones 2014). Khamsin and Carrapateena are two new copper-gold discoveries that are directly attributed to the PACE program, along with 14 other significant new discoveries that resulted from the collaborative drilling program associated with the PACE initiative (Scott and Jones 2014).

A separate collaborative drilling and geophysics program with accompanying detailed geochronology, geochemistry and petrographic studies led to significant refinements to the formation model for the supergiant Olympic Dam IOCG (iron oxide-copper-gold) deposit. Specifically, the influence of sedimentary basins on uranium deposition is now better understood (e.g. Cherry et al. 2017). The Olympic Dam mine is located in the Olympic IOCG Province along the eastern margin of the Gawler Craton (Skirrow et al. 2007) in south-central Australia, and is one the largest copper and gold resources in the world (Ehrig et al. 2012).

It is now recognized that the Olympic Dam deposit formed in a multi-stage hydrothermal-tectonic setting (Oreskes and Einaudi 1990; Reeve et al. 1990). Recent Partially Preserved Amplitude (PPA) processing of seismic data revealed steeper tectonic structures than had been imaged previously (Wise et al. 2016). This PPA processing also outlined several kilometre-scale sub-vertical zones in the vicinity of several IOCG deposits that correspond with features indicated by magnetotelluric modelling of deep conductivity. These conductive features could have been formed by hydrothermal alteration or partial-melt migration (Wise et al. 2016).

Although Canada does not currently have any producing IOCG deposits, they are strategically and economically attractive exploration targets due to their polymetallic and nuclear energy resources (Corriveau et al. 2007). The non-magmatic end-member IOCG-bearing Wernecke Breccias in the Yukon Territories (Hunt et al. 2007) fall within the proposed footprint for the CC Array. The proposed CC Array and its potential for tomographic imaging and other related projects could provide a geological and geophysical framework conducive to future economic IOCG discoveries, in the same way that the PACE program assisted in the discovery of new deposits in Australia.

### THE FUTURE OF THE EON-ROSE CONCEPT

The development of the EON-ROSE initiative is concurrent with corresponding initiatives in atmosphere-related research focused on weather, climate, and air quality, such as the *ad hoc* working group on Atmosphere-Related Research in Canadian Universities (ARRCU; Kushner et al. 2015). There is also a university-focused effort in ocean science (the Canadian Consortium of Ocean Research Universities – C-CORU: <http://www.oceannetworks.ca>). The Canadian Mountain Network is focused on sustainability of mountain environments and communities. All of these initiatives have identified areas for interdisciplinary connections between different research communities. To our knowledge, however, EON-ROSE is the first initiative to formally explore and pursue linkages between solid Earth, surface and atmospheric processes.

Experience shows that strategic planning initiatives like EON-ROSE develop over a multi-year timescale. As such, they need to be separated from the relatively short timeline of research infrastructure opportunities like the CC Array. Nevertheless, the CC Array initiative provides timely opportunities for coordinating with other scientific communities to build a nationwide program. Currently we are reaching out to solicit interest and ideas for other approaches towards using this opportunity to create new research networks aimed at understanding the coordinated working of the Earth system.

We hope that a network such as EON-ROSE will help fill many research gaps, and bring about unanticipated discoveries. It is also hoped that a broad community will be galvanized to participate and work together to maximize efficiency and consider some related ‘grand challenge’ questions. For example, what are the science questions that are likely to drive research in Earth System Science for the next 10–20 years? How can these questions be approached using new national infrastructure networks and collaboration between researchers? What

new opportunities would a network of monitoring stations and other multidisciplinary approaches offer research and how might they improve the management of resources and address societal issues? These are critical questions that face the geoscience community. We believe that an inclusive, collaborative, multidisciplinary approach within a unifying initiative is the best way forward.

If you are interested, have suggestions or questions, please contact any of the authors or other people identified on the CC Array website ([ccarray.org](http://ccarray.org)).

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