GEOPHYSICS

Hot fluids and cold crusts

Simon Kelley

Conventional wisdom says that changes to crustal rocks pushed down deep when continents collide develop over millions of years. But it seems that some metamorphism may be caused by tectonic events lasting only a decade.

The Bergen Arcs in Norway are famous for rare and rather beautiful rocks known as eclogites. Striking, coarse-grained, and characterized by large pink garnets and a green matrix rich in silicates known as pyroxene (Fig. 1), eclogites form at extremely high pressures, and are important indicators of the conditions in the deepest parts of mountain chains. In western Norway, they formed in a continental collision some 425 million years ago; since then, glaciers have ground and polished the rock surfaces to reveal the heart of the ancient collision zone, creating a wonderful natural laboratory in which to study processes that occur deep below a mountain chain — processes that must be happening today some 50 kilometres below the Himalayas.

Geologists have learnt a great deal about continental collision-zones from the Bergen Arcs[1–5], and from their geologically rapid development and exhumation. But a new study challenges current understanding: based on high-spatial-resolution analyses of measurements of argon isotopes in the mineral phlogopite, Camacho *et al.*[6] (page 1191 of this issue) propose that the partial transformation from a precursor rock-form, granulite, that characterizes the Norwegian eclogites, resulted from spasmodic, short-lived fluid-flow events lasting as little as 10 years. They also suggest that the crust at the collision zone was buried and exhumed sufficiently rapidly that it remained relatively cool during the whole cycle, which took less than 13 million years.

The eclogites of the Bergen Arcs are confined to shear zones — where rocks deform plastically as they move sideways against each other — which are also fluid pathways. Between the shear zones are regions of untransformed granulite often just tens of metres across. The Bergen Arc eclogites[1–5] formed at depths of some 60 km and temperatures of around 700 °C. Such temperatures evoke an image of very hot and plastically deforming rocks, but herein lies a paradox: though deformed at high temperatures, the Bergen Arc eclogites exhibit features more commonly associated with tectonic processes at lower temperatures closer to the Earth's surface, such as the brittle fracturing of the garnets they contain[7], and the formation of pseudotachylites[8] (rocks formed by friction melting along fractures) within them.

What is more, isotopic dating using the rubidium–strontium (^{87}Rb–^{87}Sr) technique[9] yields an age closer to the untransformed granulite lenses in keeping with a known mountain-building event 930 million years ago[10] — even though the temperatures required for eclogite formation 425 million years ago[1–5] should have obliterated any earlier signal. The paradoxical combination of granulite preservation, high-temperature eclogite formation and the brittle features of the eclogites has led several authors to suggest that the Bergen Arc granulite–eclogite transformation occurred during short-lived fluid-flow events over less than a million years[8]. But the even shorter timescales proposed by Camacho *et al.*[6] will make many geologists draw breath.

Figure 1 | Overground laboratory. Close-up view of a Bergen Arc eclogite, the subject of Camacho and colleagues' study[6], with its characteristic pink and green colouring.

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Camacho and colleagues used argon–argon (^{40}Ar–^{39}Ar) dating to measure the ages of phlogopite and amphibole mineral grains from the same untransformed granulite lenses that were investigated in the earlier ^{87}Rb–^{87}Sr work[7]. This technique works by creating the short-lived argon isotope ^{39}Ar through the irradiation of potassium (^{39}K) in mineral grains with neutrons. The age of the grains can then be ascertained from the ratio of neutron-induced ^{39}Ar to stable argon gas, ^{40}Ar, contained in them. (^{40}Ar forms from the decay of the radioactive potassium isotope ^{40}K, and its abundance indicates the elapsed time since the temperature was last high enough that argon could diffuse rapidly through the mineral, escaping at the boundaries between grains.) The particular advance of Camacho *et al.* is the use of an ultraviolet laser technique to measure profiles of ages across individual mineral grains ascertained using the argon–argon technique. The ages of between 820 and 895 million years that they find confirm the rubidium–strontium results, and demonstrate just how little the granulite lenses were affected by the later eclogite formation.

The authors[6] go on to estimate the temperature in the granulite lens during eclogite formation. Their conclusion — less than 400 °C — is a problem for the conventional interpretation of these rocks, given that a temperature of around 700 °C is required for the formation of the adjacent eclogites. Camacho *et al.* calculate that the total heating durations must have been around 18,000 years to explain the ^{40}Ar–^{39}Ar age profiles, but that individual fluid-flow events must have lasted just ten years to avoid significant heating of the granulite regions between the shear zones. This model evokes a radically different picture of the conditions during eclogite formation; but any alternative explanation would have to invoke a mechanism that explains why these phlogopites retained argon despite exceeding temperatures at which the gas would normally escape.

Camacho *et al.*[6] give us a new and rapid process for eclogite formation in the Bergen Arcs. Such rapid fluid events are not without precedent[11] and help to reconcile some of the high-temperature, yet brittle, features of these rocks. However, the very short timescales involved will make this idea controversial, as existing work on garnet[12] seems to indicate processes operating on a million-year timescale; but also, perhaps, simply because we geologists are attuned to thinking in millions of years, whereas the features we observe may be just the aggregations of many shorter events. There is still a lot to learn from eclogites — and Camacho *et al.* show us that the way forward is to focus more closely on high-resolution isotope variations in individual mineral grains and mineral interactions. ■

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