Here, only chance encounters of the energetic (up to 1.16 MeV) beta ray with electrons can produce K-shell vacancies. If necessary, a correction can be made for these X rays.

(6) The relation that may exist between ore grade and radioactive disequilibrium is not yet clearly established. In cases where samples richer in uranium are closer to equilibrium, the explanation may be the one given by Snelling and Dickson (1979, p. 116): "the greater the original amount of uranium in the sample, the greater are the amounts of uranium or daughter products that have to be added or removed to change the equilibrium ratios significantly." Among the samples we analyzed, were vein material from the Kipawa district, Quebec, which showed equilibrium activity, and pitchblende ore from the Massif Central, France, which showed distinct daughter-product deficiency.

(7) The samples we analyzed are from crystalline rocks with visible radioactive minerals, but not necessarily of ore grade. Our paper was intended for field geologists engaged in uranium exploration. We did not study rocks with "very small concentrations of uranium;" thus we do not know how common radioactive disequilibrium is in such rocks. However, uranium–lead age determination studies indicate that zircons in granites are "usually discordant" (Doe 1970, p. 11). Doe suggests (p. 55) that high-grade metamorphism reduces not only the tenor of uranium but also the lead/uranium ratios in granulites. The comprehensive interpretation of disequilibrium patterns in old common rocks remains a challenge for future research.

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The dynamothermal aureole of the Bay of Islands ophiolite suite: Discussion

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Malpas (1979) suggests that the high contact temperatures (ca. 800°C) observed at the base of the Bay of Islands ophiolite can be explained by a combination of thermal metamorphism from a hot overriding ophiolite slab and shear heating along the basal thrust of the ophiolite. This model may account for the contact temperatures but cannot explain the extremely high inverted thermal gradients (>2000°C km^{-1}) reported by Malpas (1979) from the aureole immediately below the contact. This problem is not substantially eased even if the lower contact temperatures (725°C) reported by Church (1979) are used.

Malpas (1979, p. 2097) states that ". . . Lovering's (1935) curves show that an igneous mass, of maximum dimension 2 km, with an initial temperature of 1075°C, can produce maximum temperatures of 700°C in the contact zone, which drop rapidly below 325°C 100 m from the contact." Examination of Fig. 1 demonstrates that this is true for a 2 km thick dyke intruded into country rocks at 325°C, about 60 years after intrusion. However, assuming that the mineral assemblages will record the highest temperature achieved in each part of the aureole, the recorded "thermal gradient" will be given by the *bounding envelope* of the curves in

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Fig. 1 and not by any individual curve. Any assemblages recording the initially steep thermal gradient would be overprinted by prograde reactions within a few thousand years. For the case in point, the eventual ''thermal gradient'' would be about 375°C km^{-1}, while for the more realistic case of a 5 km thick dyke (which more closely approximates the heat content of a 10 km thick ophiolite with a hot base and a cold top) a ''gradient'' of around 150°C km^{-1} would be recorded. This demonstrates that ophiolitic dynamothermal aureoles cannot be explained by any sort of passive ''hot slab'' model.

Shear heating is also inadequate to explain the observed gradients. Graham and England (1976) pointed out that the thermal gradient adjacent to a thrust plane along which shear heating is taking place is given by:

[1] $(\mathrm{d}V/\mathrm{d}x)|_{x=0} = q/2\rho\, C_p\kappa$

where: V = temperature (°C); x = distance (m) perpendicular to the thrust plane; q = heat production (J m^{-2} s^{-1}); ρ = density (kg m^{-3}); C_p = heat capacity (J kg^{-1} °C^{-1}); κ = diffusivity (m^2 s^{-1}).

Using the values for these properties given by Malpas (1979)[1] and $\mathrm{d}V/\mathrm{d}x$ = 2000°C km^{-1}, a value of q = 11 J m^{-2} s^{-1} is obtained. This requires rates of movement of about 3 m year^{-1} at 1 kbar (100 MPa) shear stress or 15 m year^{-1} at 200 bars (20 MPa). At normal geological strain rates (10 cm year^{-1}) and shear stresses (200 bars (20 MPa)) gradients of only 10°C km^{-1} can be achieved. It is evident that superimposing shear heating on the ''hot slab'' model discussed above makes very little difference to the gradient.

There are two possibilities for the steep observed gradients: (1) that the gradients are not ''real,'' and were produced from previously metamorphosed rocks by tectonic processes (e.g., tectonic thinning); (2) that the gradients were maintained by cooling at the base of the aureole either by fluid convection or shearing over cold rocks. Tectonic thinning is a possibility–strong flattening strains are certainly observed in parts of the aureole. However, the ophiolite and aureole would have to be relatively cold at the end of deformation or else the steep artificial gradient would be destroyed by prograde reactions as discussed above. The evidence for mineral growth post-S_1 (Malpas 1979; Church 1979) in the upper part of the aureole suggests that heating was occurring during deformation.

Fluid convection was perhaps active in the

[1]Note that the units used by Malpas (1979) are incompatible (e.g., J cm^{-1} s^{-1} °C^{-1} and cal g^{-1} °C^{-1}), and so his values have been adjusted accordingly.

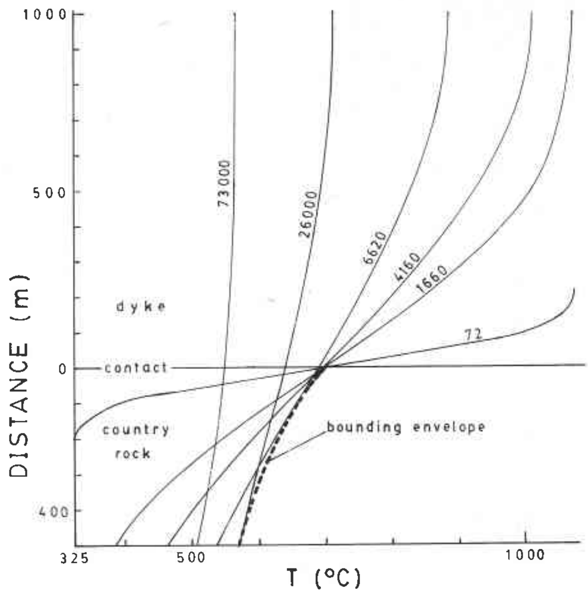

FIG. 1. Distribution of temperature within and adjacent to a 2 km thick dyke at 1075°C intruded into country rocks at 325°C. Numbers on curves are time in years. Curves taken from Lovering (1935, Fig. 2).

lower parts of the aureole where the lithologies are tuffs and sediments, perhaps from near the sediment/seawater interface. This would have the effect of contracting isotherms and steepening thermal gradients as has been shown by Norton and Taylor (1979) for the Skaergaard intrusion. The magnitude and importance of fluid convection in the present case are difficult to assess without extensive isotopic and oxidation ratio studies.

Malpas (1979) suggests that the main locus of shearing moved downwards from the base of the peridotite with time. This would result in continuous shearing of previously formed high-temperature aureole rocks over cold sediments and tuffs and would help to maintain a high thermal gradient and suppress prograde reactions in the lower part of the aureole. This situation can be modelled approximately by considering the thermal relaxation of a semi-infinite slab $x > 0$ at temperature $v = V$ whose bottom surface $x = 0$ is kept at temperature $v = 0$ (Fig. 2). The solution to this problem is given by Carslaw and Jaeger (1959, p. 59) and is:

[2] $v = V\,\mathrm{erf}((x/2\sqrt{\kappa t}))$

where t = time (s), other parameters as above.

It can be seen from Fig. 2 that if values of V = 1250°C and κ = 1.1 × 10^{-6} m s^{-1} are used, the temperature distribution after 1600 years in the lower 300 m of the model closely approximates that

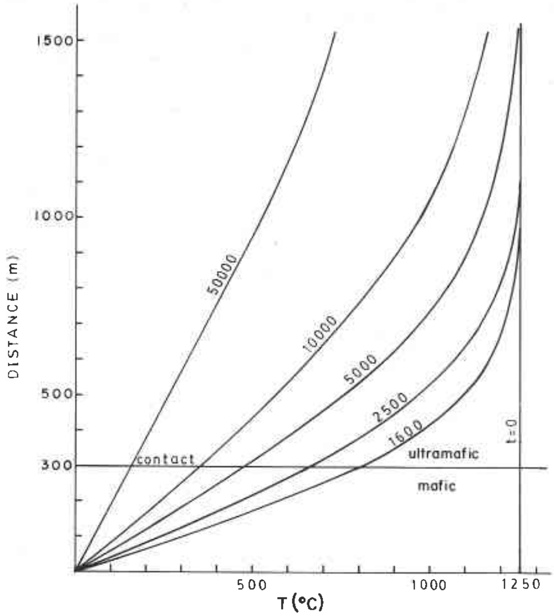

FIG. 2. Temperature distribution in an infinite slab of initial temperature 1250°C, whose bottom surface is kept at 0°C. Numbers on curves are time in years. The distribution in the lower 300 m of the model at t = 1600 years approximates that observed in the aureoles.

preserved in the aureole. From this initial distribution temperatures at all points in the aureole fall rapidly and no prograde reactions would occur. Although this model is highly artificial, it does demonstrate that by shearing over cold rocks an initially steep thermal gradient can be preserved.

The value of V = 1250°C used was chosen solely to reproduce the observed gradient in the aureole and is not considered to represent the actual temperature at the base of the ophiolite during emplacement, which was probably nearer 1000°C, as suggested by Malpas (1979). However, the emplacement model proposed by Malpas (1979) can also be used to show how the steep initial gradient and high contact temperatures may have been established. If the temperature at 5 km depth in the mantle was 1000°C, the temperature at the base of the mafic crust would have been around 500°C. Juxtaposition of peridotite at 1000°C and gabbro at 500°C would give contact temperatures of around 750°C, which could be enhanced somewhat by shear heating. If the locus of shearing then moved downwards, gabbros at 700°C might be juxtaposed with sheeted dykes at 300°C, giving contact temperatures of 500°C. In this way a composite, but nonetheless real, thermal gradient could be established, which would then be preserved by continued shearing over cold rocks.

Note that the hypothesis of downward movement of shearing is supported by the distribution of lithologies in the aureoles (e.g., Jamieson 1979) and is also precisely what would be expected if the relative strengths of the rocks are considered. Within the mantle, deformation probably occurred in a viscous shear zone, but as soon as peridotite came into contact with gabbro, deformation would shift downwards into the mafic rock due to its much lower viscosity at a given temperature (cf. Yuen *et al*. 1978). A similar shift downwards would occur when gabbro came into contact with hydrated upper crustal rocks. The work of Yuen *et al*. (1978) also suggests that the temperature of the base of the ophiolite would be kept at over 900°C by viscous shear heating up to the time it came into contact with gabbro, when deformation in the peridotite would cease. This may be necessary, since if the thrust mounted at an angle of 5°, a point at 5 km depth in the mantle would travel a distance of about 50 km over progressively colder rocks before it came into contact with the mafic crust. At 10 cm year^{-1} this would take 0.5 Ma, which would be ample time for considerable thermal relaxation.

In summary, it is considered that the emplacement model proposed by Malpas (1979) can be adapted to provide a viable mechanism for the production both of high contact temperatures and high inverted thermal gradients in ophiolitic dynamothermal aureoles.

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