the Napier complex for temperatures in the range 980–1,020 °C on a regional (> 5,000 km^2) scale[5-10]. Thus, the xenoliths described by Hayob *et al.* are neither unique nor new in their conditions of formation.

Hayob *et al.* also provide no convincing arguments for the young age of the granulite metamorphism recorded in their xenoliths; the ideal proof would have been zircon or monazite U–Pb dating. Hayob *et al.* cite a lack of retrogression and the inference of 900 °C temperatures from exsolved feldspar lamellae as evidence for recent metamorphism followed by sampling from a young, hot crust (page 267 of their paper). These arguments are tenuous, as factors other than time (for example, the access of fluids and the responsiveness of the mineral assemblage to changes in pressure or temperature) may control the extent of retrogression and re-equilibration.

With respect to retrogression and preservation of assemblages, an important aspect of the Napier complex granulites is that they cooled isobarically and stayed buried in the deep crust for at least 500 Myr and apparently for up to 2,000 Myr following the Archaean high-temperature metamorphism[3,9]. Despite this prolonged residence in the lower crust, pristine, little-retrogressed high-temperature assemblages such as sapphirine–quartz, orthopyroxene–sillimanite, sillimanite and calcic mesoperthites similar to those described by Hayob *et al.* in composition and appearance (see for example, Fig. 8 of ref. 3; Fig. 2a of ref. 11) occur throughout the Napier complex.

Thus, the textures described by Hayob *et al.* can also be found in exposed Archaean granulites which spent much of their post-Archaean history buried at least 20 km deep in the crust[9]. The textures themselves do not imply a recent metamorphism, and caution is needed to construct a syn-eruptive 'palaeogeotherm' from such crustal xenoliths. In Enderby Land, the Napier complex granulites would have been available for sampling by passing magmas during a considerable time interval. In fact, basaltic magmatism and dyking did occur in Enderby Land in the late Proterozoic[3], with little impact on the enclosing dry granulites.

The ages of the xenoliths described by Hayob *et al.* remain to be established. It would be exciting if young metamorphic ages are indeed produced using reliable techniques. The alternative, that the young magmatism is sampling unrelated and possibly much older buried granulite regions, well removed from the source of the magmatism, is equally if not more plausible.

SIMON L. HARLEY
Department of Geology and Geophysics,
University of Edinburgh,
Edinburgh EH9 3JW, UK

SIR—Hayob *et al.*[1] claim to demonstrate the formation of young high-temperature granulite-facies metamorphic rocks in the lower crust as a result of underplating by basaltic magma. Although we would not deny the possibility of recent or present-day basaltic underplating and granulite-facies metamorphism, we feel that these authors have failed to demonstrate its occurrence. Hayob *et al.*'s arguments revolve around their finding of high-temperature exsolved feldspar compositions in granulite-facies xenoliths, which have been erupted with basanitic tuffs by Quaternary volcanism in central Mexico. These feldspars (mesoperthites) yield temperature estimates of 800–950 °C for formation of the existing lamellae and host compositions, and temperature estimates of 950–1,125 °C for formation of the integrated compositions of the original feldspars. Hayob *et al.* claim that these temperature estimates set a series of precedents, and make several misleading statements, such as:

> mesoperthites yield minimum reintegrated temperatures (950–1,125 °C) that are considerably higher than those typically obtained from exposed granulites (p. 266).
> The mesoperthites provide evidence for regional metamorphism at T>950–1,125 °C, higher than any temperatures recorded previously in regionally metamorphosed rocks of undoubted sedimentary parentage (p. 267).

But there are at least two well-known terrains where both the conditions of metamorphism and mesoperthites similar to those described by Hayob *et al.* have been documented: the Lewisian complex of Scotland and the Napier complex of Antarctica; in both cases the relevant rocks are exposed on the surface, forming parts of regional granulite-facies terrains of Archaean age.

In the Lewisian case, the integrated compositions of mesoperthite grains, which coexist with antiperthite grains, suggest temperatures above 1,000 °C[12-14]. Although they occur in a granitic rock for which the proportion of igneous and metamorphic features has been debated[12,14,15] they have clearly survived a very long cooling and subsequent history before being exhumed at the surface[14-16]. Other nearby Lewisian rocks, including metasedimentary ironstones, provide evidence of temperatures of ⩾ 1,000 °C[14-17]. The Napier complex in Enderby Land includes mesoperthites and other minerals and assemblages in metasediments, which provide clear evidence of high-temperature metamorphism exceeding 900 °C[5,6,9]. This Archaean complex probably extends for >15,000 km^2 and has a long exhumation history[9,18].

The Lewisian and Napier rocks demonstrate that granulite-facies rocks with evidence of metamorphic temperatures of greater than 900 °C and mesoperthites can survive cooling to surface conditions. Although the xenolith assemblages of Hayob *et al.* may indeed never have equilibrated at temperatures below 900 °C, the authors are wrong in implying that this is because the xenoliths never experienced temperatures below 900 °C, other than when they were rapidly quenched by igneous eruption.

Hayob *et al.* assume that their xenoliths have been plucked from the base of the crust at conditions similar to the lowest pressures and temperatures (P and T) preserved in the xenoliths. Such assumptions have been questioned for xenoliths of granulite-facies rocks and even for some mantle-derived xenoliths, because the $P-T$ conditions may have been frozen into the rocks long before eruption[19,20]. The Lewisian and Napier rocks demonstrate that the $P-T$ conditions of the Hayob *et al.* xenoliths could be preserved from as long ago as the Archaean. Thus Hayob *et al.*'s assumption that their xenoliths are a product of Tertiary basaltic underplating is unwarranted; from the evidence provided, the xenoliths could have been plucked from a metamorphic complex similar to the Lewisian or Napier complex, lying at any depth in the central Mexican crust and of any age. To demonstrate very high-temperature granulite-facies metamorphism by Tertiary basaltic underplating, Hayob *et al.* need to provide direct, unequivocal evidence of the age of the relevant mineral equilibria in their xenoliths.

BEN HARTE
Department of Geology and Geophysics,
University of Edinburgh,
Edinburgh EH9 3JW, UK
ANDREW BARNICOAT
Department of Earth Sciences,
University of Leeds,
Leeds LS2 9JT, UK

HAYOB *ET AL.* REPLY — Harley and Harte and Barnicoat question our inference that granulite-facies paragneiss xenoliths from Quaternary eruptions in central Mexico preserve the highest regional metamorphic temperatures yet recorded in deep-seated crustal rocks. Elsewhere, Harley[2] has compiled $P-T$ information for more than 90 granulite terrains, only five of which record temperatures in the range 950–1,000 °C. By contrast, six of the paragneiss xenoliths from central Mexico record minimum temperatures in the range, 1,050–1,125 °C. Thus, the Mexican paragneisses record temperatures at least 100 °C higher than previously reported for regionally metamorphosed rocks; we maintain that these xenoliths do indeed record the highest regional metamorphic temperatures yet cited for crustal granulites. Our statement[1] that "the mesoperthites yield minimum reintegrated temperatures that are considerably higher than those *typically* [italics added] obtained from exposed granulites" is also

TEMPERATURES RECORDED BY EXSOLVED FELDSPARS

Granulite terrains	Ref.	Xenolith localities	Ref.
Lewisian, Scotland*			
400–420	12	El Toro, Central Mexico	
400–560	21	870–910	1
580	14		
		La Joya Honda, Central Mexico	
Adirondacks, USA†		890–960	1
300–500	22		
		Los Palau, Central Mexico	
McCullough, USA		930–960	1
600	24		
		La Olivina, North Mexico	
		840–890	29
Napier, Antarctica			
420	11	Kilbourne Hole, USA	
630	5	840–890	30
		890–920‡	30
Oaxaca, Mexico*			
420–470	25	Baidlandhill, Scotland‖	
630–710‡	25	760	31
Laramie		Partan Craig, Scotland‖	
Anorthosite, USA§		840‡	31
560	26		
		Hoggar, Algeria	
Wilson Lake, Canada		740–840‡	32
700–740‡	27		

Temperatures (°C) calculated at 1.0 gigapascals with the ternary-feldspar model of ref. 23.

*These feldspars may be of igneous origin.

†Temperatures were not recalculated as no exsolved feldspar data were given.

‡Calculated temperatures for the three components[23] do not agree within ± 50 °C.

§Equilibration temperatures from a slowly cooled igneous suite are shown for comparison, calculated at a pressure of 0.5 gigapascals.

‖ Temperatures are based on coexisting antiperthite and perthite, and probably represent peak metamorphic conditions.

valid. Harley[2] shows that most granulites record temperatures of 850 °C or lower.

The exsolved and the reintegrated mesoperthites from the Mexican xenoliths are unique in their ternary nature. Harley and Harte and Barnicoat cite several occurrences of mesoperthites in metapelites from the Archaean Lewisian and Napier complexes, which they believe are similar to those found in the Mexican xenoliths. Mesoperthites from the Lewisian complex occur in discordant granite sheets[12,21] and are probably igneous[14,21], rather than metamorphic, in origin. Moreover, a key issue of our paper was the significance of the ternary nature of the exsolved feldspar compositions, a point that Harley and Harte and Barnicoat have apparently misunderstood. As a result of the high temperatures typically achieved during granulite-facies metamorphism, alkali feldspar from exposed granulites exsolve on slow cooling to low temperatures[22].

By contrast, the failure of the host and lamellae feldspar in the Mexican paragneiss xenoliths to re-equilibrate below ~ 800–950 °C strongly suggests that the samples were not subjected to slow cooling below these temperatures. Although Harley and Harte and Barnicoat reject this argument, our conclusions are supported by many mineralogical and petrological data on natural samples from both outcropping granulite terrains and granulite xenoliths. We have recalculated temperatures[23] recorded by exsolved feldspar occurring in exposed granulites and xenoliths (see table). Feldspars that have experienced slow cooling to low temperatures (for example, in the Napier and Lewisian complexes) are invariably chemically (and structurally) reset to temperatures in the range 400–650 °C[5,11,12,14,21,22,24–26] and have not survived long exhumation histories in an unaltered form. One possible exception is the Wilson Lake complex in Labrador[27], where coexisting feldspars may record temperatures in the range 700–740 °C (see table). Calculated temperatures from this locality are extremely discordant, however, and the host–lamellae pairs cannot represent equilibrium assemblages[23].

Although extremely ternary feldspar compositions are plotted by Harley[6] on a ternary diagram for Enderby Land granulites, he gives no feldspar analyses. So it is impossible to evaluate the equilibration temperatures of coexisting host and lamellae feldspars. Using a graphical ternary feldspar thermometer[28], several of the reintegrated compositions and one exsolved(?) alkali feldspar indicate unreasonably high temperatures, in excess of 1,200°C. Harley[6] concedes that his defocused-beam analyses of mesoperthites are "indicative only", but the precise meaning of this statement is not clear. We interpret it to suggest that the reintegrations are not representative of the true compositions of the original homogeneous feldspars. Thus, we know of no mesoperthites in exposed granulites that preserve high-temperature (> 7,700 °C), equilibrium exsolutions. By contrast, coexisting exsolved feldspars found in xenoliths sometimes preserve more ternary compositions and record higher temperatures of last equilibration[1,29–32] (see table) because they have not been subjected to slow cooling at lower temperatures.

Harley and Harte and Barnicoat also question the youth of the granulite metamorphism but, in addition to the ternary feldspar compositions, geological constraints and heat flow measurements also imply a relatively young age for the last thermal event of the Mexican plateau. Mexico has been the locus of extensive Tertiary volcanism and uplift. The Tertiary Sierra Madre Occidental ignimbrite province, just west of the paragneiss xenolith localities, comprises the largest volume of erupted material exposed on Earth. These processes must have imposed a major thermal imprint on the lower crust of Mexico during the Tertiary. The central Mexican plateau is a region of high heat flow; the geothermal gradients of 20–28 °C km^{-1} estimated in our paper[1] are in agreement with gradients predicted from heat flow and crustal thickness measurements about 100 km to the north (cited in ref. 1). Although it is difficult to extrapolate gradients obtained from near-surface heat flow measurements to deeper levels, present-day heat flow measurements clearly indicate a relatively young thermal event.

J. L. HAYOB
E. J. ESSENE
Department of Geological Sciences,
University of Michigan,
Ann Arbor, Michigan 48109, USA
J. RUIZ
Department of Geosciences,
University of Arizona,
Tucson, Arizona 85721, USA

1. Hayob, J. L., Essene, E.J., Ruiz, J. Ortega-Gutierrez, F. & Aranda-Gomez, J. J. *Nature* **342**, 265–268 (1989).
2. Harley, S. L. *Geol. Mag.* **126**, 215–247 (1989).
3. Sheraton, J. W., Tingey, R. J., Black, L. P., Offe, L. A. & Ellis, D. J. *Bur. Miner. Resource Bull.* **223**, (1987).
4. Sheraton, J. W., Offe, L. A., Tingey, R. J. & Ellis, D. J. *J. geol. Soc. Aust.* **27**, 1–18 (1980).
5. Ellis, D. J., Sheraton, J. W., England, R. N. & Dallwitz, W. B. *Contr. Miner. Petrol.* **72**, 123–143 (1980).
6. Harley, S. L. *J. Petrol.* **26**, 819–856 (1985).
7. Ellis, D. J. *Contr. Miner. Petrol.* **74**, 201–210 (1980).
8. Harley, S. L. *J. metamorph. Geol.* **5**, 341–356 (1987).
9. Harley, S. L. & Black, L. P. *Spec. Publ. Geol. Soc. Lond.* **27**, 285–296 (1987).
10. Sandiford, M. A. & Powell, R. *Am. Miner.* **71**, 946–954 (1986).
11. Sandiford, M. A. *J. metamorph. Geol.* **3**, 155 (1985).
12. O'Hara, M. J. & Yarwood, G. *Phil. Trans. R. Soc.* A**288**, 441–456 (1978).
13. Ghiorso, M. *Contr. Miner. Petrol.* **87**, 282–296 (1984).
14. Sills, J. D. & Rollinson, H. R. *Spec. Publ. geol. Soc. Lond.* **27**, 81–92 (1987).
15. Barnicoat, A. *J. metamorph. Geol.* **1**, 163–182 (1983).
16. Cartwright, I. & Barnicoat, A. C. *Spec. Publ. geol. Soc. Lond.* **43**, 297–301 (1989).
17. Barnicoat, A. C. & O'Hara, M. J. *Miner. Mag.* **43**, 371–375 (1979).
18. Ellis, D. J. *Geology* **15**, 167–170 (1987).
19. Harte, B., Jackson, P. M. & Macintyre, R. M. *Nature* **291**, 147–148 (1981).
20. Harte, B. & Freer, R. *Terra Cognita* **2**, 273–274 (1982).
21. Rollinson, H. R. *Miner. Mag.* **46**, 73–76 (1982).
22. Bohlen, S. R. & Essene, E. J. *Contr. Miner. Petrol.* **62**, 153–169 (1977).
23. Fuhrman, M. L. & Lindsley, D. H. *Am. Miner.* **73**, 201–215 (1988).
24. Young, E. D., Anderson, J. L., Clarke, H. S. & Thomas, W. M. *J. Petrol.* **30**, 39–60 (1989).
25. Mora, C. I. & Valley, J. W. *Contr. Miner. Petrol.* **89**, 215–225 (1985).
26. Fuhrman, M. & Lindsley, D. H. *Geol. Soc. Am. Abstr. Prog.* **15**, 577 (1983).
27. Currie, K. L. & Gittins, J. *J. metamorph. Geol.* **6**, 603–622 (1988).
28. Lindsley, D. H. & Nekvasil, H. *Eos* **70**, 506 (1989).
29. Robinson, J. V. thesis, Univ. Calif., Santa Cruz (1988).
30. Padovani, E. L. R. & Carter, J. L. *Geophys. Monogr. Ser.* **20**, 19–55 (1977).
31. Graham, A. M. & Upton, B. G. J. *J. geol. Soc. Lond.* **135**, 219–228 (1978).
32. Leyreloup, A., Bodinier, J. L., Dupuy, C. & Dostal, J. *Contr. Miner. Petrol.* **79**, 68–75 (1982).