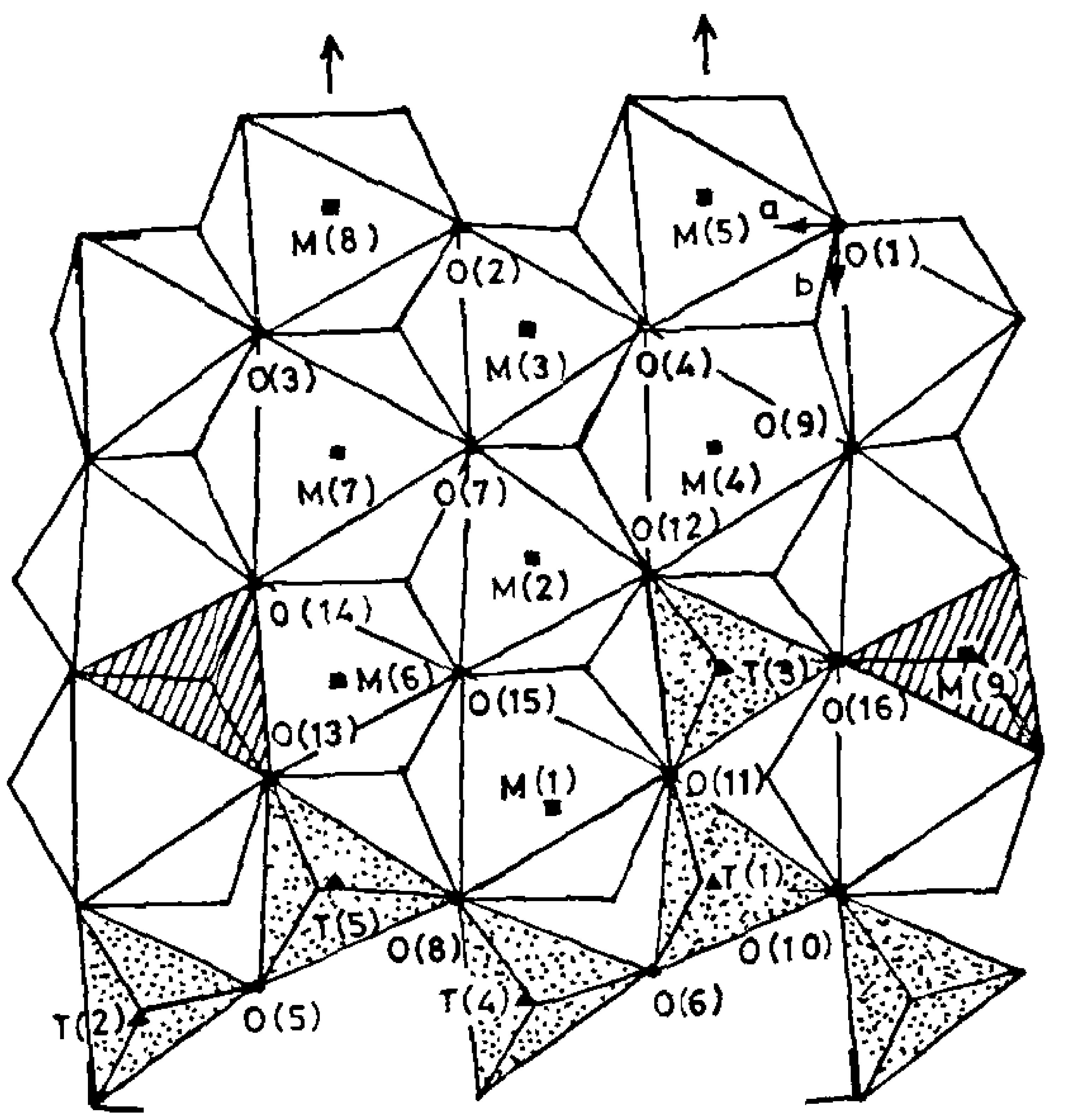

Figure 3. Polyhedral diagram of the surinamite structure. Octahedra in the walls are unshaded except M(9) and the tetrahedra are stippled The M(9) octahedra between the walls reside above the ruled margin (redrawn after Moore and Araki[3]).

possible source of Be in surinamite at this locality, whereas B and Ga are derived from the original metasediments represented as sillimanite gneisses[5] associated with the khondalites and cordierite gneisses of the study area. Beryllium-, boron- and gallium-bearing surinamite mineralization associated with the cordierite gneisses in a granulite facies terrain may reveal previously unknown geochemical features of the khondalite suite of rocks in the EGMB.

1. de Roever, E W. F, Kieft, C., Murray, Ed, Klein, E. and Drucker, W. H., *Am. Min.*, 1976, **61**, 193–199.
2. Appleman, D E. and Evans, H. T. Jr, US Nat Tech. Inf. Ser Document PB2-16188, 1970
3. Moore, P. B. and Araki, T., *Am. Min.*, 1983, **68**, 804–810.
4. Burt, D M, in *Reviews in Mineralogy* (eds Lipin, B R. and Mc Kay, G. A) Mineralogical Society of America, Washington DC, 1989, vol 21, pp. 259–302
5. Raju, K. K. V. S., in Proc. Crustal Dynamics, Indian Geophysical Union, Hyderabad, 1987, pp. 107–116.

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Evidence of garnet to spinel peridotite transition in the harzburgites of Indus ophiolite belt: An indication of their mantle origin

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The transition between garnet and spinel peridotites, caused by the reaction orthopyroxene + spinel = olivine + garnet, has been envisaged in the harzburgites of Indus Ophiolite Belt based on petrographic and geochemical studies. The reaction has been tested in the light of evidence available from phase equilibrium experiments on such transition.

THE harzburgites represent the lowermost section of ultramafic rocks, exposed as tectonically transported materials within the rocks of Dras Volcanic Group[1] or Sangeluma Group[2]. The harzburgite is made up of olivine + orthopyroxene + spinel, with modal abundance of 65 : 32 : 2% and trace amount of clinopyroxene. The harzburgites typically show a transitional texture between protogranular and porphyroclastic texture[3] or porphyroclastic texture[4]. Olivines occur both as porphyroclast (Fo 90.58–92.13) and neoblast (Fo 90.57–91.53). The former varies in grain size from 2 to 4 mm, while the latter varies from 0.5 to 1.5 mm. Majority of the porphyroclasts show development of strain shadows and kink bands. Orthopyroxene porphyroclasts are larger than olivine and vary in size from 3 to 6 mm. Both olivine and pyroxene porphyroclasts have irregular serrated grain boundaries. The pyroxene porphyroclasts are armoured by fine granular aggregates of crushed olivine and pyroxene. The porphyroclasts of orthopyroxene typically show stretching or elongation and are kinked, and often show exsolution lamellae of clinopyroxene. Besides the occurrence of clinopyroxene as exsolution lamellae, it rarely occurs as minute grains within the cluster texture; otherwise they are absent in the rock. Because of their fine grain size their individual microbe analysis is not possible. The contrast in their grain size with the rest of the assemblage and the absence of any deformational features in them raises some doubt as to whether the clinopyroxene is primary. Olivine neoblasts occurring in clusters show a close common orientation, indicating polygonization and recrystallization of former larger grains. One of the significant observations in the harzburgites is that the spinel occurs as fine-grained intergrowths with orthopyroxenes (Figure 1), in a fashion similar to the so-called finger print

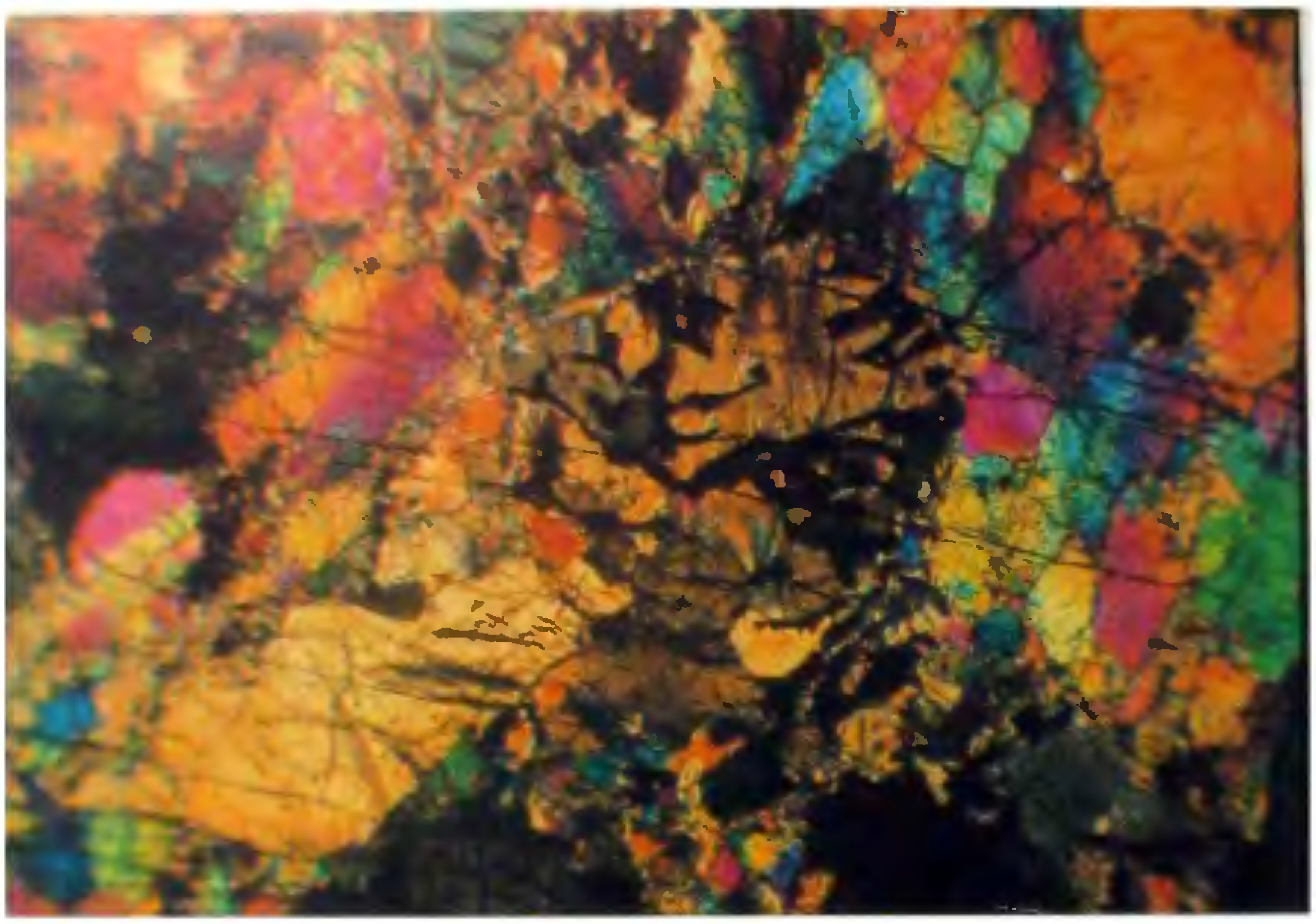

Figure 1. Photomicrograph of harzburgite showing symplectic intergrowth of aluminous spinel with orthopyroxene.

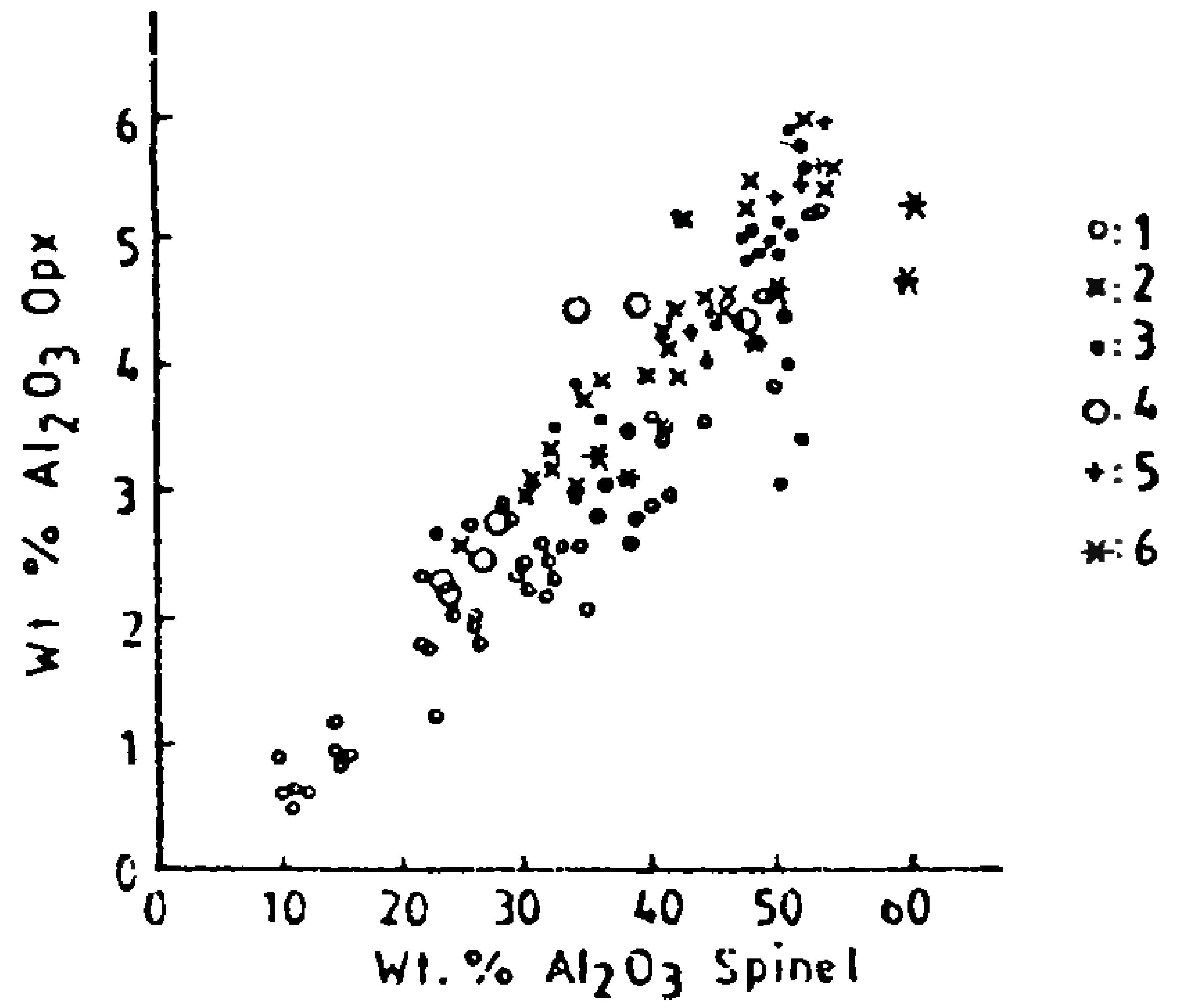

Figure 2. Plot of alumina content of coexisting enstatite and spinel in ophiolitic peridotites. 1, 'ophiolitic' alpine peridotite; 2, central Indian ridge; 3, SW Indian ridge, 4, mid-Atlantic ridge; 5, America–Antarctic ridge; 6, present investigation.

spinels[5]. The proportions of pyroxene and spinel in the cluster cannot be determined accurately because of the irregular boundaries of the aggregates. Though olivine is a dominant phase in the rock it is mostly lacking in the spinel pyroxene graphic intergrowth. The spinel is reddish-brown in colour and besides forming a part of the symplectite intergrowth also occurs as subhedral to euhedral grains interstitial to olivine and orthopyroxene. Concentration of spinel into 'holly leaf' texture was also observed in one of the samples. Composition of orthopyroxenes in clusters is similar to composition of independent orthopyroxene grains in the rock, and any textural explanation should account for the uniformity.

Orthopyroxenes are typically rich in MgO (En 89.21 to 90.32 Fs 7.67 to 9.29 Fm 0.078 to 0.092) content. The Al_2O_3 content of the pyroxene grain ranges from 2.93 to 4.46 wt%. The Mg/Mg + Fe ratio shows a general inverse relationship with the Al_2O_3 content. The spinels are typically rich in Al_2O_3 content, which varies between 32.1 and 53.58 wt% (Table 1). An increase in Cr_2O_3 with decrease in Al_2O_3 was observed form sample no. 32 to 113A, 113B. In the 100 Cr/(Cr + Al) vs 100 Mg/(Mg + Fe) diagram[6] they occupy the field of spinels from ultramafic xenoliths. The Cr and Mg contents behave inversely. The spinel analysis shows them all to be highly aluminous and magnesian, but appreciable amount of chromium and total iron are also present. They are probably best regarded as ferroan chrome spinel.

The strong correlation between Al_2O_3 content of orthopyroxene and spinel found in Figure 2, cannot be just a coincidence but suggests Al partitioning between pyroxene and spinel and supports their co-genetic nature.

The spinel–orthopyroxene symplectite intergrowth texture is seen to be a notable feature of lherzolite/harzburgite nodules as well as alpine peridotites. This texture has been attributed to a variety of origins, viz:

(i) Primary crystallization from pools of melt concentrated during partial fusion[5]: However, pyrometamorphic textures are absent in the studied samples. Besides, the preservation of such original texture seems unlikely considering the deformation that the rock has undergone.

(ii) Mechanical concentration of spinel and pyroxene during deformation[3]: This can explain the concentration of spinel into 'holly leaf' textures. But it cannot explain its strict association only with pyroxene and not with olivine. Alumina partitioned between spinel and enstatite as indicated by the strong correlation cannot be a mere coincidence.

(iii) Exsolution of spinel and diopside from a former aluminous pyroxene[3]: This requires non-stoichiometric conditions for both spinel and pyroxene. Besides, higher values of Al_2O_3 of almost 24 wt% are envisaged for the original pyroxenes. The temperature pressure values required to equilibrate such pyroxenes are unrealistic. The observed high chrome content of the spinel in the sample is in contrast to such an origin.

The absence of plagioclase in the rock under study as well as the low calcic nature of the small clinopyroxene and the high Cr_2O_3 content of the spinel in the cluster texture preclude the possibility of the cluster texture being a product of the reaction between forsterite and anorthite. Similarly, the reaction forsterite + Al-clinopyroxene = spinel + diopside fails to explain the low modal abundance of clinopyroxene in the rock (< 1 vol.%), the strict association of spinel only with orthopyroxene (enstatite) and not with diopside, as well as the observed strong correlation between Al_2O_3 of the orthopyroxene and that of the spinel.

The only feasible explanation is their formation by the reaction

$$\text{pyrope} + \text{olivine} = \text{orthopyroxene} + \text{spinel} + \text{clinopyroxene}^{7}.$$

Table 1. Electron microprobe microanalysis of orthopyroxenes and aluminous spinels from harzburgites, Ladakh Himalaya

	Orthopyroxene Sample No					
	113A		113B		32	
	c	m	c	m	c	m
SiO_2	54 66	55.22	56.31	55.78	54 92	55 21
TiO_2	00.03	—	00 06	—	00 10	00 02
Al_2O_3	04.09	03 93	02 93	02 73	04 46	04 16
Cr_2O_3	00 90	00 86	00.66	00 74	00 40	00 55
FeO	05.30	05 35	05 04	05 91	06 10	06 05
MgO	33 64	33 80	34 40	35 53	33 98	34 13
CaO	01 10	01 05	00 76	00 40	00.80	00 47
Na_2O	—	00 02	00 01	00 02	00 02	00.01
K_2O	—	—	00 02	—	—	—
MnO	00 07	00 12	00.13	00 14	00 20	00.12
Total	99 79	100 36	99 32	101 25	100.97	100 72
Wo	02 12	02 01	01 45	00 74	01 50	00 88
En	89.84	89 83	90 82	90 60	89 21	89.98
Fs	08 04	08 16	07 67	08 66	09 29	09 13
Fm	00 0821	00 0833	00 0778	00 0872	00.0922	00 092
t	00 0953	00 0911	00.0675	00 0964	00 0964	00 1049
$t = 0\ 5\ (Al + Cr - Na)$						
			Aluminous spinels			
TiO_2	—	00 03	00 06	00 06	00 60	00 60
Al_2O_3	44 17	41 71	32 14	34.53	53.58	53 54
Fe_2O_3	01 34	00 46	00 80	01 59	—	—
FeO	13 36	12 54	13 44	13 75	10 23	10 62
Cr_2O_3	24 35	28 15	37 66	35 06	16 75	16 21
MgO	16 56	16 87	15 19	15.56	20 05	19 68
MnO	00 18	00 13	00 23	00 15	00.06	00 10
ZnO	00.23	00 23	00 19	00 07	—	—
Total	100 19	100 12	99 71	100 77	101 27	100 75

This appears to be attendant upon a fall in pressure from garnet peridotite facies to spinel peridotite facies conditions and is consistent with the experimental results[8,9]. The presence of clinopyroxene is additional to the phases in the reaction

pyrope + forsterite = enstatite + spinel

originally proposed[10], due to the addition of CaO to the system[11].

For garnet to react and yield pyroxene with the observed value of $t = 0.06$ the product should have 0.306 molar fraction of spinel[7], which is in good agreement with the measured results (0.30) in the present case. Higher values of t in some samples correspond to a lower modal abundance of spinel in the samples, and larger percentage of independent orthopyroxenes in the rock account for a low modal abundance of spinel. Besides, there is an absence of olivine and garnet in the cluster, indicating the complete reaction of garnet and olivine and conversion of original garnet peridotite assemblage to spinel peridotite. The postulated original garnet may be slightly rich in chrome content, similar in composition to the 'chrome pyrope' (> 4 wt% Cr_2O_3 and higher CaO) variety found in the garnet peridotite xenoliths of Montana diatreams[12]. This will also account for the Cr-rich nature of the spinel and also the small amount of the low calcic clinopyroxene present in the symplectite cluster. The orthopyroxene analyses includes the exsolution lamellaes of clinopyroxene; even then the CaO content in these orthopyroxenes rarely exceeds 1 wt%, which in itself is a proof to consider the low calcic nature of the minute clinopyroxenes in the symplectite. More direct evidences for the olivine–garnet reaction are many[13–15].

The transition from garnet to spinel peridotite as exhibited by the texture may occur during heating or decrease in pressure[13]. Occurrence of pyroxene exsolution lamellae in the rock indicates extensive cooling and so a pressure-induced reaction is more likely[7]. Certainly, such an diapiric movement of the mantle would be in keeping with the evidence of deformation-induced recrystallization textures observed in the sample. It has been shown that the reaction enstatite + spinel = forsterite + pyrope takes place in the pressure range 15–35 kbar at temperatures from 800 to 1600°C (ref. 10). A series of experiments on 'pyrolite' compositions define the stability fields of spinel peridotite and garnet peridotite and the reaction occurs at around 20 kbar in the temperature range 900–1300°C (ref. 16). The boundary is sensitive to the amount of R_2O_3 (Al_2O_3, Cr_2O_3) (ref. 17). Single pyroxene geothermometry[18] gives a temperature range of 1050–1100°C. The pressure values obtained from the Al_2O_3 isopleths and other parameters[19] range between 15 and 25 kbar, which agree well with the experimental values[20,21]. Thus, the garnet–olivine reaction model fits the rock better than any other alternative hypothesis. The reaction described here is reasonably interpreted as an adjustment of the primary high-pressure assemblage to a lower-pressure environment. A decrease in the confining pressure from 50 to below 20 kbar would move the garnet out of its stability field[14].

Garnet peridotite would be subject to pressure decrease during tectonic uplift or mantle upwelling; this may have been responsible for the formation of such symplectite texture. The cluster texture may, therefore, be an indicator of mantle convection. Occurrence of spinel–pyroxene symplectite intergrowth in the alpine peridotite or ultramafic xenolith can be taken as an evidence of garnet to spinel peridotite transition in the mantle.

1. Searle, M. P., *Trans. R. Soc. Edin. Earth. Sci.*, 1983, **73**, 205–219.
2. Srikantia, S. V. and Razdan, M. L., *J Geol. Soc. India*, 1980, **21**, 523–545.
3. Mercier, J. C. C. and Nicolas, A., *J. Petrol*, 1975, **16**, 454–487.
4. Pike, J. E. and Schwarzman, E C., *J. Geol.*, 1976, **85**, 49–61.
5. Dawson, J. B. and Smith, J. V., *Phys Chem. Earth*, 1975, **9**, 339–350
6. Irvine, T N. and Findley, T. C., in *The Ancient Ocean Lithosphere*, Dept. E M S., 1972, vol. 43, pp. 97–126.
7. Smith, D., *J. Geol.*, 1977, **85**, 476–482
8. MacGregor, I. D., *J. Geol.*, 1965, **64**, 126–134.
9. Cohen, L. H., Ito, K. and Kennedy, G. C., *Am. J Sci.*, 1967, **265**, 475–518.
10. MacGregor, I. D, *Yb. Carnegie Instn Washington*, 1964, **63**, 157.
11. Dawson, J. B., Powel, D. G. and Reid, A M., *J. Petrol*, 1970, **11**, 519–548.
12. Heran, B. C. Jr, and McGee, E. S., *US Geol. Surv. Bull.*, spl. paper, 1983, **1604**, 1–33.
13. Wallace, R. C., *Contrib. Mineral. Petrol.*, 1975, **49**, 191–199.
14. Reid, A. M. and Dawson, J. B., *Lithos*, 1972, **5**, 115–124.
15. Varne, R., *J. Petrol.*, 1977, **81**(1), 1–23.
16. Green, D. H and Ringwood, A. E., *Earth Planet. Sci. Lett.*, 1967, **3**, 151–160.
17. MacGregor, I. D, *Phys. Earth Planet. Inter.*, 1970, **3**, 372–377.
18. Mercier, J. C. C, *Am. Mineral*, 1976, **61**, 603–661.
19. Mysen, O. B, *Am. Mineral*, 1976, **61**, 677–683.
20. MacGregor, I. D., *Am. Mineral*, 1974, **59**, 110–119.
21. Dankwerth, P. A. and Newton, R. C., *Contrib. Mineral. Petrol.*, 1978, **66**, 189–201.

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