

Paragonite paragenesis from the garnet granulites of the Jijal complex, Kohistan, N. Pakistan

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ABSTRACT. Chemistry of six white micas from the high-pressure garnet granulites of Jijal is presented, together with trace elements, refractive indices, and $2V_{\alpha}$ for one. The micas are rich in the paragonite component (over 93%), with one analysis having the highest 100 Na/(Na+K) ratio (98.5) so far reported. The paragonite is not a stable mineral of the granulites but was overprinted on the granulites at about 505–540 °C and 8–9 kbar (suggesting a depth of 30 km).

THE Jijal complex is a wedge-like mass of garnet granulites and alpine-type ultramafic rocks together covering an area of ~200 km² along the Indus in Kohistan (35° 5' N., 72° 55' E.). The complex was tectonically emplaced along the 'Main Mantle Thrust' considered to be an extension of the 'Indus Suture Line' which marks the subduction of the Indian Plate under the Tibetan Landmass. To the south of the MMT are found Precambrian to Palaeozoic sialic metasediments and granites of the Indo-Pakistan Plate. To its north are found variously metamorphosed basic, intermediate, and acidic plutons and volcanic rocks with minor metasediments, bounded on the north by the main Karakorum Thrust with associated ophiolitic melange. The entire association between the two thrusts was postulated to constitute the crust and mantle of a Cretaceous–Early Tertiary island arc (Tahirkheli *et al.*, 1979; Bard *et al.*, 1980; Jan, 1980), but the possibility of a continental margin was also hinted at by Jan and Kempe (1973) and Jan (1977).

The Jijal complex is principally composed of garnet granulites. The ultramafics (harzburgite sub-type of Jackson and Thayer, 1972) mostly occur in a sheet up to 4 km wide along the southern margin of the complex. Both rock types have undergone granulite-facies metamorphism, the estimated conditions being 690–770 °C, 12–14 kbar for the granulites and 800–850 °C, 8–12 kbar for

the ultramafics (Jan and Howie, 1981). The granulites are considered to be gabbros/norites with some troctolites, allivalites, pyroxenites, and diorites differentiated (some layering still preserved) from a high-alumina tholeiite (calc-alkaline) magma, metamorphosed during the collision of the Indian-Asian landmasses and uplifted during the later Himalayan orogenic episodes.

The granulites are divisible into those with essential plagioclase and those with little or no plagioclase, reflecting differences in bulk chemistry. Garnet + plagioclase + clinopyroxene + quartz + rutile ± hornblende ± epidote is the commonest assemblage but the 'plagioclase-free' rocks are composed mainly of one, two or three of the phases garnet, pyroxenes, amphibole, epidote. Retrograde metamorphism has produced amphibole, chlorite, epidote, and paragonite. Petrographic studies suggest that the retrograde minerals and veins represent assemblages of amphibolite- to greenschist-facies (Jan, 1980). The paragonite development has usually taken place in shear zones but the mineral is also found in some pegmatitic facies of the granulite and in epidote-plagioclase-hornblende ± garnet pegmatite veins some of which contain epidote up to 35 cm long and paragonite over a centimetre across.

This paper deals with the occurrence and chemistry of six paragonites which are amongst the most sodic reported so far. The available experimental data have been used in deducing the physical conditions prevailing during the growth of paragonite. Five of the micas were analysed by microprobe and one by wet chemistry.

Analytical techniques. Separated concentrate of SI291 was analysed by combining modern and classical methods. SiO₂ was determined gravimetrically, FeO by titration, H₂O⁺ by the Penfield

method, TiO_2 and P_2O_5 colorimetrically, and F by the rapid method of Hall and Walsh (1969). The rest of the elements and total Fe_2O_3 were determined by atomic absorption. Standard solutions and suitable international laboratory standards were used for reference. Refractive indices were determined by the dispersion method and 2V by the Mallard-Tobi method on separated grains.

The microprobe analyses were made with a Cambridge Scientific Instruments Microscan 5 microprobe at Leicester at an accelerating voltage of 15 kV and a specimen current of 25 nA. In two-spectrometer wavelength dispersive analyses, alkalis were analysed first. The method used eliminates errors in spectrometer repeatability but relies upon specimen re-positioning repeatability. Standards used were natural wollastonite for Si and Ca, natural jadeite for Al and Na, natural rutile and microcline for Ti and K, respectively, MgO for Mg, and pure iron for Fe.

Petrography of the paragonite-bearing samples. N621, N632, N638, SI291, and SI284 are medium-grained and moderately to well-foliated metabasalts composed of green hornblende, epidote, paragonite, quartz, and rutile and with some relict garnet stable in the earlier granulite-facies metamorphism. The first one is free of plagioclase, SI632 and SI638 have rare plagioclase, SI291 has some, whilst SI284 has common plagioclase. N632 is a mafic schist with a more highly developed fabric (foliation) and with almost cataclastic-type quartz. N618 is very different from the rest in that it consists of abundant epidote (over 50%), quartz, rare plagioclase, and paragonite. It is a homogeneous rock with no tectonic fabric, white in hand specimen but containing inclusions of garnet and hornblende; the sample comes from a vein in hornblende. Sample N638 contains penninite developed after garnet. Mineral analyses in SI291 reveal that its garnet is $\text{Alm}_{4.3}\text{Pyr}_{31.3}\text{Gro}_{21.1}\text{And}_{3.1}\text{Spe}_{1.5}$, epidote $\text{Ps}_{14.6}$, and hornblende is tschermakitic (Jan and Howie, 1981), whilst the plagioclase is An_{26} .

Texturally the paragonite ranges from radiating aggregates of blades in gabbroic rocks with weak tectonic fabric (SI284, N638) through intermediate cases of deformation with some radiating and some foliated, oriented crystal aggregates (N621, SI291), to mafic schists which have been flattened by differential compression around the garnets (N632). The paragonite has mostly grown in the siliceous matrix of the gabbros surrounded by quartz grains, and occurs especially as radiating clusters sparring late quartz (N638) and in foliated seams of quartz (N632). In N618 and SI291 it forms within quartz and along quartz-epidote boundaries.

The following evidence indicates that the para-

gonite did not form as a stable phase in the anhydrous garnet granulites: 1. It generally occurs in shear zones. 2. It commonly shows cross-cutting relations with other minerals, even with late quartz. 3. It never occurs in rocks with the assemblage garnet-clinopyroxene-plagioclase-quartz, but rather in rocks with much hornblende and well-formed epidote. 4. Whereas the anhydrous granulites typically contain cloudy or saussuritized plagioclase, the paragonite is associated with fresh unaltered plagioclase.

On this evidence we conclude that the paragonite developed as a retrograde product together with hornblende, epidote, and quartz, following the high-pressure granulite-facies metamorphism caused by subduction against the Indus suture. Thus the paragonite should have formed at lower P and T conditions than the 12–14 kbar and 690–770 °C of the granulite metamorphism (Jan and Howie, 1981).

Since the clinopyroxene of the granulite is not rich in Na, the only mineral that could have donated Na for paragonite formation is plagioclase. The breakdown of this plagioclase and of clinopyroxene would have contributed the components needed for the growth of hornblende, epidote, and quartz.

Analyses of the paragonite. Chemical compositions of six paragonites, together with trace elements, refractive indices and $2V_z$ for one, are presented in Table I. The H_2O^+ content of the wet chemically analysed sample (SI291) is distinctly lower than that of paragonite analyses presented by Deer *et al.* (1963) and Sekino *et al.* (1975). (H_2O was determined by the Penfield method on only 0.25 g of material left after wet analysis and is clearly underestimated, as revealed by the high Y total (4.30) and low OH + F (3.2) when the analysis is recast on the basis of 24(O,OH,F).) The trace elements in this mica are not unusual apart from a high V content.

A characteristic feature of the Jijal micas is their enrichment in the paragonite component. Feininger (1980) reported paragonites with up to 100 Na/(Na + K) = 93 in pelitic schists, glaucophane schists, and eclogitic amphibolites from the Andes of Ecuador, which he considered to have formed at 580 °C and 13 kbar and Baltatzis and Wood (1979) reported micas with a 100 Na/(Na + K) ratio of 93 in chloritoid schist in Scotland considered to be stable up to 600 °C and 7.5 kbar. Even more sodic paragonite (100 Na/(Na + K) = 96.6) was described by Sekino *et al.* (1975) from Kabo, Japan; the mica occurs in close association with albite and jadeite in serpentine and was closest to the end-member paragonite analysed at that time. Table I shows that the Jijal micas are all exceptionally sodic

TABLE I. Analyses of paragonites from the Jijal complex, Kohistan

No. of anal.	3 N632	5 N621	SI291	3 N618	5 N638	23 SI284
SiO ₂	45.81	46.05	46.89	46.47	45.99	46.34
TiO ₂	0.09	0.16	0.28	0.14	0.18	0.13
Al ₂ O ₃	38.87	38.70	38.97	39.15	37.92	38.48
FeO	0.51	0.70	0.60	0.24	0.82	0.83
MgO	0.13	0.10	0.23	0.15	0.11	0.19
CaO	0.52	0.53	0.87	0.56	0.56	0.43
Na ₂ O	7.04	7.14	6.93	7.19	7.23	7.32
K ₂ O	0.72	0.51	0.45	0.45	0.42	0.17
Total	93.68	93.89	99.45*	94.35	93.22	93.89
Number of ions based on 22(O)						
Si	5.966	5.984	5.986	5.990	6.022	6.013
Al	2.034	2.016	2.014	2.010	1.978	1.987
Al	3.933	3.910	3.851	3.941	3.874	3.898
Ti	0.008	0.016	0.027	0.013	0.017	0.013
Fe	0.056	0.077	0.064	0.026	0.090	0.090
Mg	0.025	0.019	0.044	0.029	0.021	0.037
Ca	0.072	0.073	0.119	0.077	0.079	0.060
Na	1.777	1.800	1.715	1.802	1.835	1.842
K	0.120	0.085	0.074	0.074	0.071	0.028
Z	8.00	8.00	8.00	8.00	8.00	8.00
Y	4.01	4.02	4.02	4.01	4.00	4.04
X	1.97	1.96	1.91	1.95	1.99	1.93
100 Na	93.7	95.5	95.9	96.1	96.3	98.5
Na+K						

SI291 wet chemically analysed by M.Q.J. Remainder were analysed by R.N.W. using WD microprobe except SI284—18 analyses by ED microprobe, 5 analyses by WD microprobe.

* SI291 contains Fe₂O₃ = 0.38% (making 0.036 in Y), H₂O⁺ = 3.82%, F = 0.05%, MnO = 0.00%, and (in ppm) Co = 4, Cr = 25, Cu = 25, Li = 12, Ni = 26, Pb = 5, V = 182, Zn = 6, α = 1.577, β = 1.607, γ = 1.612 (all \pm 0.002), $2V_{\alpha}$ = 28 to 49°.

with SI284 being the most paragonite-rich so far recorded (100 Na/(Na+K) = 98.5). We found no evidence of zoning between core and rim of 9 grains in SI284.

The refractive indices of the paragonite SI291 match those of the paragonite from Kobo, Japan (Sekino *et al.*, 1975). However, a surprising feature of this mica is the variation in the values of the optic axial angle. Determinations of $2V_{\alpha}$ (by Mallard-Tobi method) in 47 grains range from 28 to 49° with a mean of 39°, 33 of the determinations yielding values between 35 and 44°. Variations in $2V$ in paragonite, possibly reflecting different structural states (cf. Deer *et al.*, 1963), have been reported in different areas but we are unaware of such a variation in different grains of a single hand specimen. In fact, variations up to 9° have been noted here within different parts of a single strained grain and between sections normal to, and oblique to, the cleavage within a grain (? again strained). The observed variation in the optic axial angle may reflect structural distortion arising from strain.

Conditions of metamorphism. Fig. 1 shows the approximate conditions of metamorphism under

which the paragonite grew in the Jijal rocks. The system Na₂O-Al₂O₃-SiO₂-H₂O was investigated by Gусynin and Ivanov (1971), Chatterjee (1972, 1974), and Chatterjee and Froese (1975). The reaction paragonite + quartz = albite + Al-silicate + H₂O is stable at < 500°C at 1 kbar to about 660°C at 9.5 kbar. Above 9.5 kbar P_{H_2O} the reaction terminates due to formation of melt. The assemblage paragonite + quartz + albite melts between 600 and 650°C at 17 to 8 kbar P_{H_2O} (Huang and Wyllie, 1974). Thus the paragonite paragenesis in Jijal must have formed at temperatures lower than those of the typical Jijal granulite (garnet + clinopyroxene \pm plagioclase) assemblage, i.e. 690–770°C (Jan and Howie, 1981).

The Ca-alkali distribution in the plagioclase and hornblende in SI291 yields a temperature of 560°C by both the methods of Perchuk (1966) and Spear (1980). The reaction paragonite + hornblende = albite + garnet + zoisite occurs at about 570°C at 15 kbar to 530°C at 8 kbar (Dobretsov and Sobolev, 1975). It is thus likely that the upper temperature limit of the paragonite paragenesis is approximately 560°C.

The presence of the right-hand assemblage of the reaction lawsonite + albite = zoisite + paragonite (Dobretsov and Sobolev, 1975) suggests temperatures in excess of 400°C at pressures over 7.5 kbar. The occurrence of hornblende + plagioclase more calcic than albite (i.e. An₂₈ in SI291), and the absence of greenschist paragenesis indicate that the Jijal paragonite assemblage formed during amphibolite-facies conditions, requiring a minimum temperature of about 520°C at 8–10 kbar (Winkler, 1965; Sobolev *et al.*, 1967; Dobretsov and Sobolev, 1975).

For a temperature of 530°C or more, a minimum pressure of about 8.5 kbar is suggested for the Jijal rocks by the right-hand paragenesis in the reaction margarite + plagioclase = paragonite + zoisite + quartz (Franz and Althaus, 1977). Omphacite and jadeite are absent in the paragonite-bearing rocks, although the bulk composition of these basic rocks would be generally appropriate, and this constrains the maximum pressure limits. An absolute maximum pressure of 14–15 kbar is provided by the reaction albite = jadeite + quartz (Holland, 1979). In fig. 1 the jadeite₂₉ isopleth for omphacite in equilibrium with albite and quartz in mafic schists from the Appalachians is after Laird and Albee (1981). The paragonite-bearing rocks are sodic meta-gabbros and mafic schists and yet glaucophane is significantly absent. This is important because glaucophane-bearing mafic schists are common only 30 km to the west on the Indus Suture. The glaucophane stability field of Maresch (1977) is indicated on fig. 1 and this places an upper

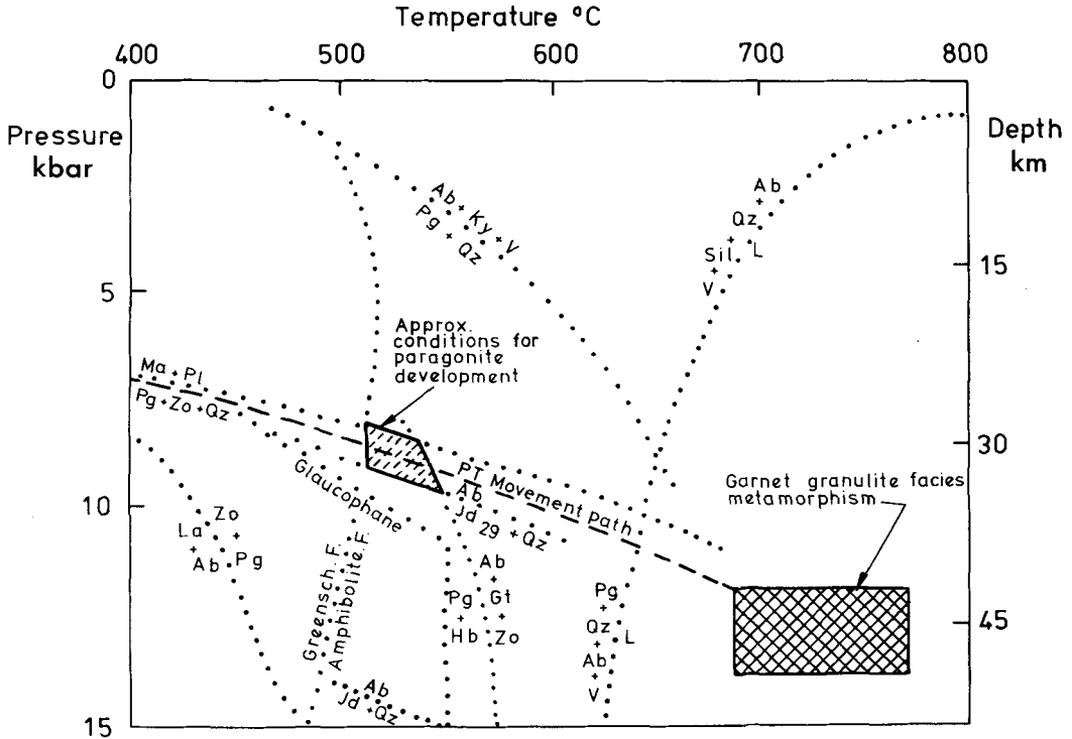


FIG. 1. Temperature-pressure/depth diagram showing the estimated conditions of granulite-facies metamorphism, of paragonite formation and the movement path of the Jijal complex. Melting curve of paragonite-quartz-albite-H₂O and albite-quartz-sillimanite-H₂O after Huang and Wyllie (1974). Reactions paragonite + quartz = albite + kyanite + H₂O after Chatterjee (1972, 1974) and Chatterjee and Froese (1975); lawsonite + albite = zoisite + paragonite, and paragonite + hornblende = albite + garnet + zoisite after Dobretsov and Sobolev (1975); albite = jadeite + quartz after Holland (1979); albite = jadeite₂₉ in omphacite + quartz after Laird and Albee (1981); glaucophane stability limit after Maresch (1977); and paragonite + zoisite + quartz = margarite + plagioclase after Franz and Althaus (1977). Approximate boundary of greenschist-amphibolite facies after Winkler (1965), Sobolev *et al.* (1967) and Dobretsov and Sobolev (1975).

pressure limit of 9.5 kbar and 11 kbar at 510 and 550° respectively. With the above constraints our best estimate for the *PT* conditions of the Jijal paragonite-bearing rocks is 8–9.5 kbar and 510–550°C (area indicated on fig. 1).

The movement path in *PT* space of the Jijal Complex is indicated on fig. 1. It is possible that this represents the equilibration path consequent upon uplift from its high-pressure granulite-facies metamorphism in the Indus Suture. Further studies of vein systems in the Jijal Complex will be useful to corroborate this hypothesis.

Conclusions. Paragonite occurs in stable association with epidote, hornblende, quartz, plagioclase, and rutile in the metagabbroic rocks of the Jijal complex. The micas are rich in the paragonite component (100 Na/(Na+K) > 93) with one analysis being the nearest to the paragonite end-member so far reported (98.5). 2V determinations

in one sample show considerable variation not only in different grains but also within different parts of a single grain of paragonite. These variations probably reflect structural distortions caused by strain. Based on recent experimental data applicable to the Jijal rocks it is estimated that the paragonite-bearing paragenesis formed in the range 510 to 550°C and 8 to 9.5 kbar. The granulite-facies metamorphism occurred at 690–770°C and 12–14 kbar (Jan and Howie, 1981), suggesting a depth of ~45 km. The paragonite-bearing paragenesis is a retrograde overprint that took place at a depth of 30 km, possibly during uplift of the Jijal complex against the Indus Suture.

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