PETROGRAPHY OF THE JIJAL COMPLEX, KOHISTAN

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ABSTRACT

This paper presents a detailed petrography of the garnet granulites and garnet-free ultramafic rocks which constitute a > 150 sq. km. tectonic block at Jijal, Indus Kohistan. The granulites are classified into (1) those with essential plagioclase, and (2) those with little or no plagioclase; the two types are a consequence of bulk chemical rather than environmental differences (Jan and Howie, in prep.). A total of 17 mineral assemblages have been identified, with garnet + clinopyroxene + plagioclase + quartz + rutile ± hornblende ± epidote being the most widespread. The plagioclase-free granulites are generally composed of two or three of the minerals garnet, clinopyroxene, hornblende, and orthopyroxene or epidote. The granulites were produced by high-pressure metamorphism of a series of hypersthene gabbros with some more and some less silicic rocks.

The ultramafic rocks have alpine-type features but, unlike most alpine-type ultramafic rocks, they are dominated by diopsidites (with or without olivine); dunites, harzburgites aud websterites together make less than 50% of the > 40 km slab. The granulites and ultramafic rocks are considered to have originated in the Tethyan lower crust-upper mantle before they were metamorphosed during the collision of the Indian-Asian masses. The granulites were intruded in the granulites as plastic material after the main metamorphism but before the two were tectonically brought in their present surroundings.

INTRODUCTION.

The Jijal complex, comprising garnet granulites and alpine-type ultramafic rocks, covers an orea of more than 150 sq. km. The ultramafic racks occupy the southern part of the complex but the granulites are locally also present at their southern margin. The western and eastern limits of the complex are not known because of the inaccessibility of the area. It appears that to the east the rocks extend beyond the Indus river into Hazara tribal territory whilst to the west they may reach up to, but not beyond, the drainage divide between the Indus and Swat valleys.

The complex is fault-bounded to the north as well as the south; it seems that it is a tectonic block or wedge bounded by faults on all sides. The southern fault is an extension of the main fault separating the Swat schists and granitic gneisses from amphibolites of the Kohistan complex to the southwest of Jijal. In the Jijal-Patan area, the amphibolites occur to the northeast of Patan and are separated from the garnet granulites by a fault running along the approximately N-S course of the Patan stream.

The garnet granulites cover over 60% of the investigated part of the Jijal complex. In addition to the main mass and local bodies in the southern part, lenses of granulite have also been noted in the ultramafic rocks. The available evidence indicates that the latter were emplaced into the previously metamorphosed granulites. The contact relationship between the two, however, is far from simple. The southern granulite patches have sheared contacts which are retrogressively altered; the northern contact does not seem to be sharp or sheared but appears to be gradational and interfingered (Qureshi and Jan, 1977). The complicated nature of the contact here is exacerbated by similar mineralogy; both groups of rocks are represented by pyroxenites near the contact and it is very difficult to distinguish between them in the field. Nevertheless, there are certain differences in the geochemistry of the two types and in their clinopyroxene compositions, and more systematic sampling and selective analysis of rocks in the vicinity of the contact may be needed. However, if the ultramafic rocks were emplaced as 'plastic' mush in the garnet granulites, as suggested by Qureshi and Jan (1977), interfingering and xenolithic incorporation of one into the other is to be expected. Lenses of ultramafic rocks have also been found in the granulites; those occurring along the Patan stream may have been squeezed from depth along the fault.

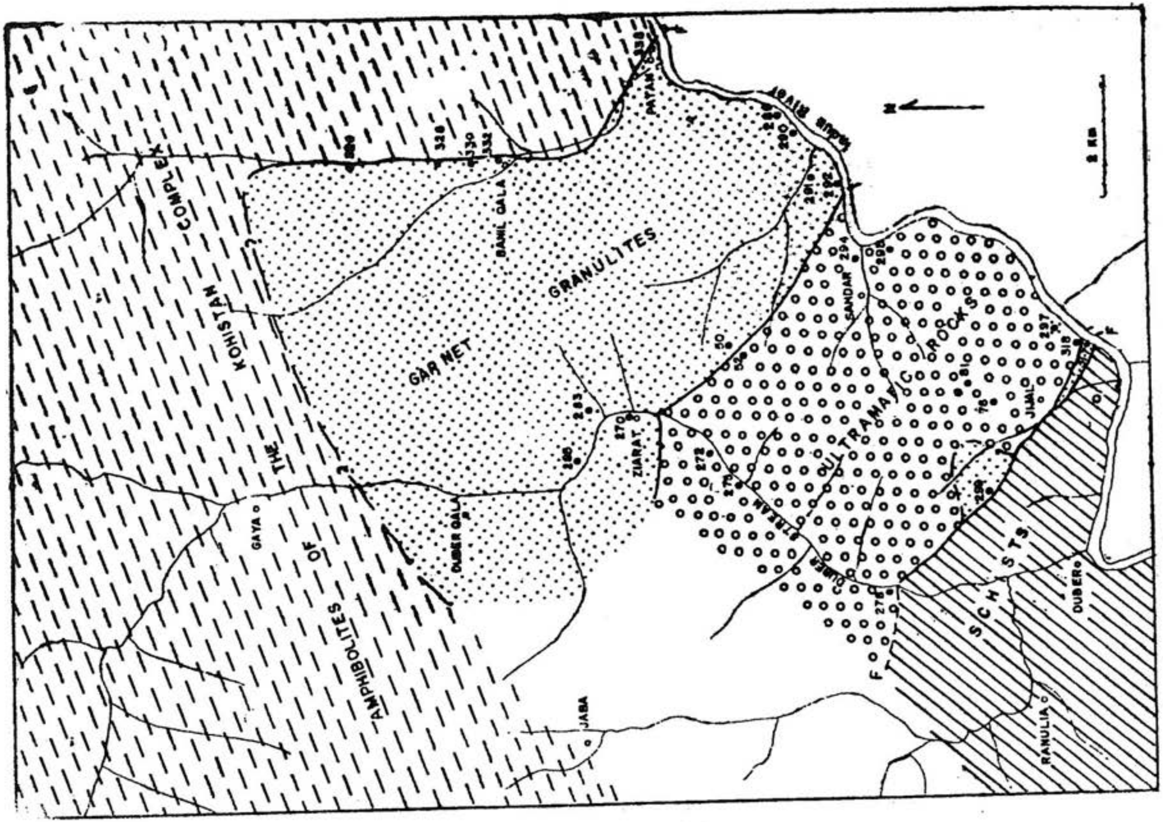

Fig. 1. Simplified geological map up the Jijal complex. Numbers show the locations of analysed rocks. (From Jan, 1977).

Megascopic features

The granulites of Jijal are characterised at most outcrops by an abundance of garnet. They can be broadly classified into two types : (1) those in which plagioclase is an important constituent, and (2) those in which plagioclase occurs either as an accessory mineral or is absent. The presence or absence of the essential plagioclase is a function of bulk chemistry; the more basic rocks (poor in SiO_2 and Na_2O) are free of plagioclase whilst less basic and intermediate rocks contain essential plagioclase. Rocks in the first type make up most of the granulites and are generally gneissose and medium-grained, whilst those of the second type are non-gneissose and medium- to coarse-grained. Based an various combinations and proportions of the constituent minerals, Jan (1977) identified 17 mineral assemblages; the most common assemblage is : intermediate plagioclase + garnet + clinopyroxene or/and hornblende + quartz + rutile ± epidote. This assemblage is typical of the high-pressure granulite facies (Green and Ringwood, 1967).

The rocks are locally porphyroblastic, with garnet crystals up to 9 cm across, locally arranged in trains or clusters. Some of the porphyroblasts are surrounded by a felsic and/or mafic envelope up to a few centimetres thick; more rarely, medium to coarse crystals of greenish yellow epidote may also occur on their margins. Thin veins containing varying combinations and proportions of garant, hornblande, epidote, feldspar, quartz and, rarely, carbonate mineral(s) and (?) clinopyroxene are common. In some places the rocks contain feldspathic veins studded with garnet porphyroblasts (Pl. 1b) the host rock having been amphibolitised for a few centimetres on both sides of the veins. In two places these rocks contain paragonite in small outcrops locally attaining a pegmatitic aspect.

Some of the rocks are banded (Pl. 1a), especially in the Patan stream where all gradations from dominently non-banded gneissose to banded types are seen. Straining and crushing/granulation of the minerals, as seen in thin section, suggest that most of the banded types owe their structure to shearing along the fault plane. However, in others it cannot be decided whether the banding is relict 'layering' or a product of metamorphic differentiation. In some places there are crude bands rich in either garnet, feldspar, or hornblende/ clinopyroxene, and some pagamatitic bands a few contimetres thick and parallel to the foliation; these appear to be due to metamorphic differentiation.

The type 2 granulites are dominated by 'bimineralic' and trimineralic rocks—garnetites, garnetiferous hornblende rocks, pyroxenites—and rare garnet-hornblende-(clino)zoisite rocks. They are common in the southern part of the granulite mass although garnetites and, rarely, hornblende rocks have also been noticed along the Patan stream. These rocks are not restricted in size and can occur in masses a few hundred metres broad and considerably longer. Qureshi and Khan (1972) have in fact shown a 250 to 600m broad belt of type 2 rocks extending from the Indus river to the Duber stream and beyond along the northern margin of the ultramafic mass.

Whilst the garnet- and pyroxene-rich rocks are uniformly medium-grained, the hornblende-rich types vary in grain size; the variation may be gradual or abrupt within a single body of rocks (Jan and Tahirkheli, 1969) and, in rare cases, the hornblende crystals reach 6½ cm in length. Although in most cases the type 2 rocks form distinct bodies of their own, they occur locally in a confused mixture: patches and bands of garnetites, pyroxenites and type 1 granulites occurring in the hornblende rocks and vice versa. Mixing is particularly common between the hornblende- and garnet-rich rocks; such features are clearly seen in the road-cuts between Patan and Jijal.

Features observed in thin section

The granulites of Jijal are generally medium-grained (but at one place very coarse-grained, as shown in Plate Id), 'hypidioblastic' to xenoblastic rocks but in some the garnet is idioblastic. Triple points and straight to curved mineral boundaries are common. In addition to the common garnet porphyroblasts, hornblende, clinopyroxene and, rarely, (clino)zoisite may also occur in large grains. Some of the rocks are mylonised and these may contain rounded porphyroclasts of garnets and, rarely, of clinopyroxene and clinozoisite; in others mineral straining is common.

Modal compositions of the representative rocks are presented in Table 1. The most common rocks are composed of plagioclase, garnet, clinopyroxene, with lesser quantities of quartz, rutile and/or opaque minerals (Pl. 2a). The type 2 rocks are essentially composed of one to three minerals but some have more than this number of essential minerals. The following assemblages have been identified, (Jan and Howie, in preparation):

Type 1—plagioclase-bearing granulites (all containing minor rutile and/or opaque minerals)

1. plagioclass-garnet-clinopyroxene-quartz ± hornblende
2. plagioclass-garnet-clinopyroxene-quartz ± epidote
3. plagioclass-garnet-hornblende-qnartz ± epidote
4. plagioclass-garnet-hornblende-clinopyroxene-epidote-quartz
5. plagioclass-garnet-hornblende-epidote-paragonite-quartz

Type 2—granulites with little or no plagioclase

Garnet-rich types (some with rutile and/or opaque mineral(s)):

6. garnet-clinopyroxene-hornblende ± plagioclase
7. garnet-clinopyroxene ± spinel and hornblende
8. garnet-hornblende
9. garnet-hornblende-epidote ± clinopyroxens ± plagioclase ± quartz

Hornblende-rich types (all containing rutile and/or opaque mineral (s)):

10. hornblende-garnet
11. hornblende-garnet-clinopyroxene (+ spinel in one rock)
12. hornblende-epidote-garnet ± plagioclase

Pyroxene-rich assemblages (most have opaque mineral(s) but not rutile; hornblende, when present, is minor):

13. clinopyroxene-garnet ± hornblende
14. clinopyroxene-orthopyroxene ± garnet ± hornblende
15. clinopyroxene-epidote-garnet

(Clino)zoisite-rich types (containing minor rutile and/or opaque mineral(s) and, rarely, sphene):

16. (clino)zoisite-hornblende ± garnet and quartz
17. (clino)zoisite-garnet-clinopyroxene-quartz ± hornblende

The status of epidote is confusing and it requires discussion before the other minerals are described. The following three modes of occurrence have been found in the Jijal granulites for the minerals of the epidote group :

a) As tiny prisms of (clino)zoisite intensely developed after plagioclase in some rocks; common epidote grown after garnet; and as a reaction product between the minerals, usually involving the plagioclase; all of these are retrograde products.

b) In a few rocks, occurring to the south of the ultramafic mass near the fault, (clino)zoisite may eonstitute over 50% of the rocks (e. g., assemblages 16 and 17 which are rare in the main mass of the granulites); some or probably all of the clinozoisite is a retrograde product. In some of these rocks the latter forms acicular grains (in rare cases radially grown) and penetrates large, well-formed (clino)zoisite and hornblende grains. Such growths are common in hydrothermal veins and indicate the availability of sufficient water for their formation. However, some grains of the epidote mineral in these rocks are well-formed ,and have sharp crystalline boundaries against other minerals (Pl. 3a); these may belong to the third type of occurrence discussed below.

c) Epidote (100 $Fe^{3+}/(Fe^{3+} + Al) = 14.6$ and 19.3) occurring in apparent equilibrium with coexisting fresh plagioclase. In some cases, the mineral is sieved with vermicular or rounded quartz and (in SI 326) is distinctly zoned. In these there is little doubt of the primary (metamorphic) nature of the epidote mineral. However, it is still debatable whether or not such epidote - bearing assemblages are iso-facial with the other assemblages; it is possible that such rocks are completely re-equilibrated garnet granulite assemblages (at lesser depth and hence lower P, T) during the upward transport of the rocks. This would also be the cause of the paragonite occurrence in some of the epidote-hearing rocks. However, it is thought here that at least in some rocks the epidote is prograde and the epidote-bearing assemblages iso-facial with the rest. (Clino)zoisite has been reported from experiments at high P and T on brown-hornblande mylonite from St. Paul (Millhollen and Wyllie, 1974). Den Tex and Vogel (1962) have suggested the recognition of a clinozoisite granulite subfacies whilst Manna and Sen (1974) have reported a large amount of "prograde epidote in an unusual variety of garnetiferous pyroxene granulite from Bengal. In the Jijal area, epidote minerals have not been found in the rocks containing orthopyroxene.

In many rocks the plagioclase is intensely cloudy or, saussuritised and full of tiny prisms of (clino)zoisite, whilst in a few patches of epidote with vermicular quartz also occur in the feldspar. White mica, quartz, and albite are among the alteration products. In some rocks where the plagioclase is fresh, its composition (based on maximum symmetrical extinction angle on albite twins) is near An_{40}, but in rare cases it is calcic andesine. Twinning is usually poorly developed and is on the albite and/or pericline/acline laws; some rocks almost completely lack twinned plagioclase whilst in others the twin lamellae may be bent. In one rock the plagioclase (and epidote) is zoned and twinned on combined Carlsbad-albite-pericline/acline twins.

Garnet, a ubiquitous mineral in the Jijal granulites, is pinkish in colour and composed essentially of pyrope (28 to 46 mole per cent), almandine (27 to 43 %) and grossular (17 to 28%). In some rocks it tends to be idioblastic but in most has only a few crystalline faces. Zoning is either absent or minor but inclusions of other minerals are common; in some rocks the clinopyroxene and rutile are present in this form only. Most garnet grains contain fractures along which have grown epidote, chlorite and, less commonly, bluish-green amphibole and quartz, the alteration may be only marginal or extensive (Pl. 2b). In some cases thin veins of epidote, chlorite and, rarely, plagioclase and quartz also occur.

The clinopyroxene ($Mg_{44-34}\ Fe_{5-17}\ Wo_{51-49}$) is usually grsenish and sometimes pleochroic. It is aluminous (up to 10% Al_2O_3) but not omphacitic. In a few rocks (e.g., garnet websterites) it is colourless or has a purplish tint probably due to a higher Ti content. Minor alteration along its margins and fractures to an amphibole is common; in one case it has a margin of chlorite and epidote probably developed due to a retrograde reaction with the plagioclase. Orthopyroxene, with the single exception of one type I granulite (SI 328), has been found only in websteritic rocks. It is usually strongly pleochroic and bronzite to

TABLE 1. MODAL COMPOSITION OF REPRESENTATIVE GARNET GRANULITES

Sample	No of points counted	Thin section(s)	Plg	Gar	Cpx	Amph	Epi	Qz	Rt	Ore	Others
SID 50	8878	1	46.8	25.1	21.3	...	0.6	4.6	0.2	1.3	0.2
SI 270	3949	1	...	16.8	77.1	5.7	...	...	...	0.4	...
SI 281	8639	1	...	7.2	...	57.2	33.5	...	2.0	0.1	...
SI 289	5655	1	...	4.8	0.1	90.8	1.6	0.2	0.8	1.2	0.5
SI 290	3413	1	24.7	45.5	13.4	...	5.2	10.4	0.6	...	0.3
SI 292	2912	1	...	71.3	20.7	7.4	...	...	Tr	0.5	0.2
SI 326	4614	1	22.7	30.6	4.5	32.5	5.8	2.9	0.6	...	0.3
SI 332	4384	1	46.6	25.6	17.1	1.8	2.5	3.8	...	2.3	0.3
SI 338	12000	2	39.2	28.3	19.2	0.2	0.2	12.4	0.3	0.2	Tr

Locations of the samples shown on Fig. 1.

hypersthene in composition. Its occurrence in SI 328 (assemblage 1, Pl. 2c) is restricted to unstable relics, suggesting that the operative pressures were in excess of 8 to 10 kb (Green and Ringwood, 1967; Winkler, 1974). The relationship can be expressed by the following reaction :

orthopyroxene + plagioclase → clinopyroxene + garnet + quartz
(low pressure) (high pressure)

The amphibole of the Jijal rocks is hornblendic and generally brownish green but in some it is pale or bluish green; some have a purplish (?) Ti-rich hue. Bluish green amphibole is also a common secondary product after garnet and, rarely, after pyroxene. Whether or not all the bluish green amphibole, at least in the garnetites, is secondary is difficult to say. In some rocks the amphibole is full of rounded or vermicular quartz granules; in the hornblende-rich samples it contains rutile and brownish black to black blades of an opaque mineral which seem occasionally to have a preferred orientation in two or three directions. The inclusions may be uniformly distributed or they may occur only in the central parts of the grains. Chemical analyses of five amphiboles suggest that, according to Leake's (1968) classification, they are magnesio hornblendes in the garnet-rich rocks, ferroan pargasite in the hornblende-rich rocks, and alumino-tschermakitic hornblende in the paragonite-bearing rocks. Like the amphiboles of the granulite facies rocks, they are rich in Al_2O_3 (up to 16.3%) and Al^6 (up to 1.06).

The opaque mineral grains appear in most cases to be ilmenite, sometimes showing marginal or complete alteration to leucoxene, sphene, or rutile. Some of the rocks also contain magnetite whilst a few have a sulphide (? pyrite) that is marginally oxidised/hydroxidised to a red or black material. Sphene has not been found as an independent phase except in some sheared and retrograde and a few (clino)zoisite-rich rocks. Rutile is a common accessory in most rocks in the form of independent grains, as well as in association with ilmenite. The quartz is usually strained and, in rare cases, forms rather large 'patches'. In one rock, retrograde scapolite has developed at the expense of the plagioclase.

Green and Ringwood (1967) have grouped the granulite facies rocks into low-, intermediate-, and high-pressure types. The first is characterised by the association olivine + plagioclase and by the occurrance of cordierite; the second type by the association orthopyroxene + plagioclase ± clinopyroxene (typical of the pyroxene granulites of Swat, discussed in a following paper) and by the incompatibility of olivine + plagioclase; and the third by the association garnet + clinopyroxene + quartz and the incompatibility of hypersthene + plagioclase. A survey of the literature indicates that the high-pressure is much rarer than the intermediate-pressure type. The occurrence of high-pressure granulites, reported in the literature from SE Germany, southern Poland, western Czechoslovakia, NW Spain, Ghana, and South Harris, NW Scotland, has been reviewed by Green and Ringwood (1967). In the following paragraphs, a brief comparison of the Jijal rocks with similar rocks from other areas is made.

Davidson (1943) and Dearnley (1963) have reported assemblages 1 and 13 from South Harris. Eclogite-like rocks, represented by assemblage 6 (without plagioclase), 7, and 8 have been described by Pinus *et al.* (1970) from NE Siberia, and those represented by assemblage 1 from east Sudeten (Poland) by Kozlowski (1958); and eclogite amphibolites (assemblage 9, without plagioclase and quartz) and eclogite from Puerto Cabello, Venezuela (Morgan, 1970). Morgan (1974) has also described garnet pyroxenites similar to assemblages 6 and 13 (with plagioclase) from Sabah, Malaysia. Garnet pyroxenites and garnet granulites (with or without spinel, plagioclase, amphibole, and mica) have been reported as xenoliths in basaltic rocks and as layers in alpine-type peridotite massifs. Irving (1974) has listed 28 localities for the former and nine for the latter types of occurrence.

Comparison of other high-pressure granulites with those of Jijal illustrates two points : (a) that there is a greater range of mineral assemblages in the Jijal rocks than in those from other areas, and (b) that the Jijal rocks may form the largest mass of garnet granulites so far described. Although the granulite complex at Cabo Ortegal, NW Spain (Den Tex and Vogel, 1962; Den Tex *et al.*, 1972) covers a larger area than the Jijal complex, the garnet-plagioclase-clinopyroxene assemblage from the former area is less extensive. The two areas have remarkable similarities in some respects; many of the assemblages are common to the two areas, although in Spain the epidote- and hornblende-bearing assemblages are more common, epidote is more abundant, and garnetites have not been reported. Both areas have ultramafic rocks associated with the granulites; in Spain pelitic assemblages and eclogite also occur.

Concluding remarks

The Jijal granulites were probably derived from a differentiated series of noritic gabbros with some pyroxenites, troctolites, olivine gabbros, feldspathic allivalites and hypersthene-quartz diorites. These rocks originally evolved from an Al-rich, alkali (mainly K) - poor magma of tholeiitic nature (? Ti-depleted oceanic tholeiite) in the Tethyan crust/upper mantle or, less likely, in a continental margin. They were metamorphosed at great depth under high-pressure granulite facies conditions during the collision of the Indian-Asian landmasses, and finally uplifted to their present site during subsequent Himalayan orogenic episodes. The granulites have distinctly higher densities (3.2 to 3.5) than those (about 3.0) of the rocks surrounding the Jijal complex. Various methods of geothermometry and geobarometry suggest that the granulites were equilibrated at 670°—770°C and 12—14 kb, suggesting a depth of more than 40 km for the metamorphism (Jan and Howie, in preparation).

THE AlPINE-TYPE ULTRAMAFIC ROCKS

Megascopic features

The ultramafic rocks (Fig. 1) occur in a NW-trending, north-dipping body over 4.5 km wide and at least 10 km long (Jan and Tahirkheli, 1969). They may be taking a southwesterly turn (? due to folding along the fault plane) at their western end, or there may be another body of similar rocks to the southwest of Chopra (Qureshi and Khan, 1972). The second possibility is more likely; there may be a number of ultramafic bodies emplaced along the thrust, the largest being the 7 × 1 km lensoid serpentinised mass near Shangla. A small lens of serpentinised ultramafic rock occurs within the schists outcropping along the road just to the south of the main mass (and main fault). A number of small serpentinised bodies also occur along the Patan stream, probably emplaced and/or squeezed tectonically along the northern fault.

The rocks are hard, massive, brownish to green or grey, and medium-grained; some of the pyroxenites are coarse-grained. There is no clear distinction of top, bottom or chilled margins. The contacts between various units may be sharp or gradational; some of the pyroxenites contain lenses of dunite with sharp contacts (Pl. 3d). Serpentinisation, although widespread, is not intense in the main body; however, the southern margin is apparently more altered due to shearing. Intense shearing is also seen, near the contact, in the country rocks (graphitic, calcarsous, and greenish micaoeous schists) and in the garnet granulite patches. It is not clear to what extent they have been affected by the emplacement of the ultramafic mass along the thrust fault; much of the shearing could be due to faulting.

Some of the peridotites contain coarse-grained clinopyroxenite veins up to a few centimetres thick and lacking chilled margins. They seem to be secondary and produced by Ca and Si metasomatism. They are more common in a harzburgite in Duber stream, arranged parallel to subparallel, and at a few metres distance from each other. At places the peridotites also contain coarse crystals of pyroxene that are apparently arranged in crude, thin bands at a high angle to the NW trend of the main ultramafic mass. Some of the dunites and peridotites contain bands (up to 2 cm × 5 m) and streaks of chromite (Pl. 3b, 4d). They are generally folded, some of the bands being variously squeezed and, locally, tapering suddenly at their ends. The general trend of the less folded streaks and bands is, again, at a high angle to the NW trend of the body. Thus if the spinel concentrations and the coarse pyroxens streaks represent some kind of original structure (? stratification), then the ultramafic rocks are not in structural harmony with the garnet granulites.

Features observed in the section

The Jijal ultramafie rocks are mainly represented by clinopyroxenites; dunites, peridotites, and websterites make up less than half the outcrops. The pyroxenites may or may not contain olivine, whilst some of the dunites have a small amount of clinopyroxene. Orthopyroxenites and lherzolites have not been found. Cr-rich spinel of a brownish colour is a typical accessory in the olivine-rich rocks but green spinel has been noted in one rock. Most of the rocks contain magnetite formed during serpentinisation; it is not certain whether there is any primary magnetite.

A harzburgite (SI 275), based on a count of 5995 points in one thin section, is composed of 86.5% forsterite, 10.1% enstatite, 1.1% serpentine, 1.0% diopside, 0.9% Cr-spinel and 0.4% talc. A pyroxenite vein (SI 275a) in this rock, based on 3890 counts in one section, is composed of 86.4% diopside, 12.4% serpentine, and 1.2% opaque minerals (probably mainly Cr-spinel). The ultramafic lenses along the Patan stream are peridotitic, composed of olivine and clinopyroxene. One of the sheared lenses in the garnet granulite here contains serpentine, an opaque mineral, green spinel, (?) carbonate, and abundant tremolite developed along numerous fractures in olivine and clinopyroxene.

The abundance of clinopyroxenites in the Jijal mass is in marked contrast to other alpine-type ultramafic complexes, where peridotites and dunites are the main rock types (Jackson and Thayer, 1972). Detailed investigation and systematic close sampling, especially to the east of the Indus, is needed before a final assessment can be made of the relative abundance of the clinopyroxenites. However, it is possible that: (1) the Jijal rocks are either a dismembered part of a much larger 'normal' alpine ultramafic mass; (2) olivine-rich rocks are present at depth or to the east; or (3) the diopsidites are a product of large-scale Ca and Si metasomatism at high temperatures. The pyroxenite veins, mentioned above, are an example of the latter phenomenon.

The ultramafic rocks are medium- to coarse-grained and generally allotriomorphic. Deformation is illustrated by the frequent fractures, non-uniform strain extinction, and hour-glass textures and kink bands in pyroxene and olivine grains. In some places the rocks are intensely granulated (Pl. 4b, c) and have a mortar texture, whilst in a few the granulation is confined to the grain margins due probably to movement of the individual grains against each other. In general the olivine is more granulated than the pyroxene and it is possible that in the latter adjustment in response to strain took place by movement along the cleavage planes In some of the rocks the pyroxene forms large ophitic 'patches' enclosing olivine grains. The chromite streaks and bands (Thayer, 1970) and the ophitic pyroxene may be suggestive of a magmatic history for the rocks.

The clinopyroxene is colourless or, probably due to a higher content of Cr, faintly green. In a few it contains a set of brownish black (?) exsolved opaque mineral grains or lamellae parallel to the cleavage; In rare cases, another set is seen at a high angle to the first. In even rarer cases, (?) exsolved lamellae of an orthopyroxens also occur. Qureshi and Jan (1977) determined the compositions of three clinopyroxenes optically whilst anther four were chemically analysed by Jan (1977 a). All are diopsides with composition ranging from $En_{49.9} Fs_{2.8} Wo_{47.3}$ to $En_{48} Fs_{6.0} Wo_{46.0}$. The orthopyroxene ranges from En_{91} in a harzburgite to En_{82} in a websterite. The olivine (one chemical and eight optical determinations) ranges from $Fo_{92.1}$ to $Fo_{88.5}$.

Characteristics of the alpine-type ultramafic rocks have been reviewed by many authors. Tectonic fabrics, Mg-rich olivines and pyroxenes (generally with a Mg/Fe ratio of 9/1), common concentrations of chromian spinels (Thayer, 1960, 1967, 1969; Jackson and Thayer, 1972) and little compositional variation in the rocks (Moores, 1969), are among their special features. The Jijal rocks share these characteristics; they are also devoid of plagioclase, micas, and primary amphibole. Den Tex (1969) subdividsd the alpine peridotites into two genetic classes, the ophiolitic or truly alpine-type, and the root-zone peridotites found in very high grade metamorphic terrains in deeply eroded mountain roots. The Jijal rocks should probably be placed in the second group although this does not necessarily mean that they are genetically related to the garnet granulites.

Moores and MacGregor (1972) have classified alpine peridotites into various categories on the basis of their mode of occurrence. The 'conformable bodies in regionally metamorphosed terrains' are in part the 'root-zone' peridotites of Den Tex (1969). "Many of these masses display garnet peridotite assemblages and pronounced effects of deep-seated recrystallization and equilibration. It is presently unknown whether all masses represent deformed mafic-ultramafic complexes or whether some actually are the product of mantle diapirism into deep crustal levels" (Moores, 1973).

Alteration

Most of the Jijal rocks are more or less serpentinised (Pl. 4c) but intense serpentinisation is lacking except in local patches and along shear planes and veins (Pl. 3c). The alteration is selective and within a single thin section some grains of a mineral species may be fresh whilst others are strongly serpentinised, probably as a result of differential shearing prior to alteration. In general, the olivine is more affected than pyroxene; this is in agreement with the observation that the former is more granulated (sheared) than the latter. However, according to Wicks, 1969 (reported in Moody, 1976) the different degree of alteration (olivine > orthopyroxene > clinopyroxene) probably reflects a different rate of serpentinisation in a low P, T environment. The strong serpentinisation in the more highly granulated rocks suggests that the process was activated after cataclasis and (?) emplacement. On the other hand, in some schistose, and other less sheared ultramafic rocks of Jijal, the serpentine displays some degree of parallel arrangement (Pl. 4b) suggestive of pre- or syntectonic development.

Based on the study of crystal form and birefringence, most of the rocks seem to contain more than one serpentine mineral. In addition to the common chrysotile and antigorite, minor quantities of lizardite, bastite, and serpophite have also been noted in the rocks (Qureshi and Jan, 1977). Coleman (1971), Ashraf *et al.* (1972) and many other workers have also reported more than one type of serpentine in serpentinites. The presence of antigorite indicates that the serpentinite has undergone prograde metamorphism or that the peridotite was serpentinised in a higher P, T regime than would yield lizardite and chrysotile (Coleman, 1971; Moody, 1976).

In most cases, the serpentine is accompanied by small amounts of granular magnetite but in some there is very little of this mineral, suggesting either that the iron present in the pyroxene and olivine was expelled or, more probably and as suggested by the absence of magnetite veins and concentrations, was accommodated in the structure of the serpentine minerals. The amount of iron substitution in serpentine is a function of temperature and low fO_2 , with increased (prograde) temperature enhancing magnetite formation (Moody, 1976). In a few rocks, however, the amount of magnetite is much more than is likely to have been produced by the alteration of Mg-rich silicates. In one dunite (SI 318; Pl 5a), magnetite is the main mineral formed along abundant microfractures. It appears that the solutions responsible for serpentinisation in such cases may have contained iron of either external origin or undergoing redistribution within the rock body.

In rare cases, anhedral magnetite grains are surrounded by up to three shells of (?) different serpentine minerals showing radial growth. It cannot be said with certainty whether the magnetite grains existed first, the serpentine forming later around them, or whether both were the product of breakdown of olivine/pyroxene in such a way that the iron migrated towards the centre and the Mg and Si components outwards. In some cases, however, the magnetite content is too high to have resulted by the second process.

In addition to serpentine, a number of rocks contain talc and tremolite; some contain carbonate and a few green to yellowish (?) chlorite. The talc appears to replace serpentine in some cases; that steatisation follows serpentinisation has been noticed in other areas (Jahns, 1967, p. 155). The sequenee of tremolite-serpentine formation is not clear. In some rocks the amphibole seems to have formed later; in one rock the serpentine schistosity is clearly cross-cut by a later schistosity developed in tremolite. However, in a few rocks the amphibole is replaced by serpentine.

Concluding remarks

Like most other alpine-type ultramafic rocks (Den Tex, 1969) the Jijal ultramafites have aiso passed through a complex history of evolution. Their present mineralogy appears, again, to be a product of regional metamorphism (800°—850° C, 8—12 Kb). They do not seem to be related magmatically to the Jijal granulites and were probably intruded in them as crystalline mushes after both had undergone the high-grade regional metamorphism at different sites, but before the two were tectonically transported to their present site (Jan, 1977b; Jan and Howie, in preparation).

There are significant differences in the chemical analyses of the two types of rocks and in the trends of their clinopyroxenes and it will be unwise to suggest that they have been derived from the same magma (Jan, 1977a). Similarly it cannot be suggested that the ultramafic rocks and garnet granulites of the Jijal complex were derived from the same magma which produced the pyroxene granulites of Kohistan. The noritic and pyroxenitic rocks in the latter have significant differences in major and trace element chemistry with the basic granulites and pyroxenites of the Jijal complex. Over 500 joint poles plotted separately for ultramafic rocks and granulites (Qureshi and Jan, 1977) also show different patterns. It appears that in the granulites the joints were produced in at least two phases whilst those in ultramafic rocks in one or two phases. The stresses have a noughly N—S orientation.

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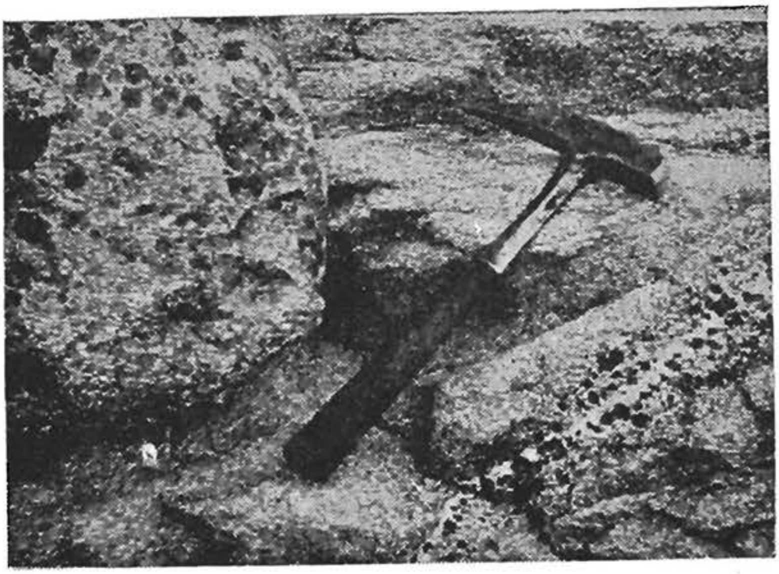
Plate 1

A



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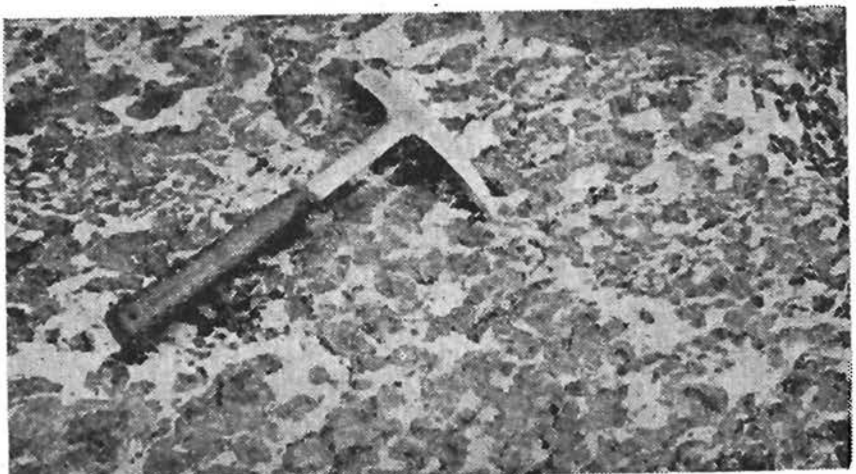

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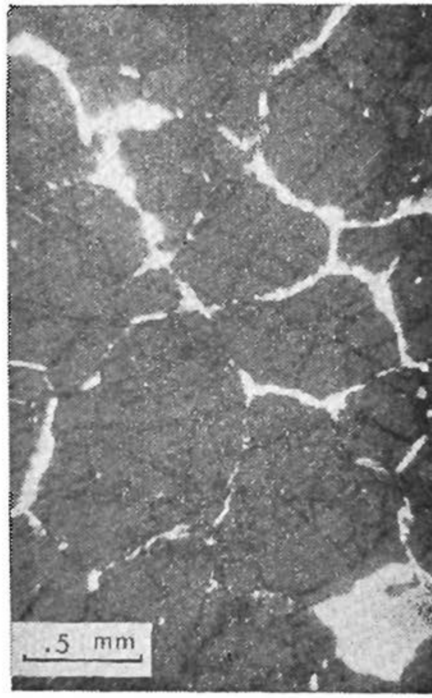

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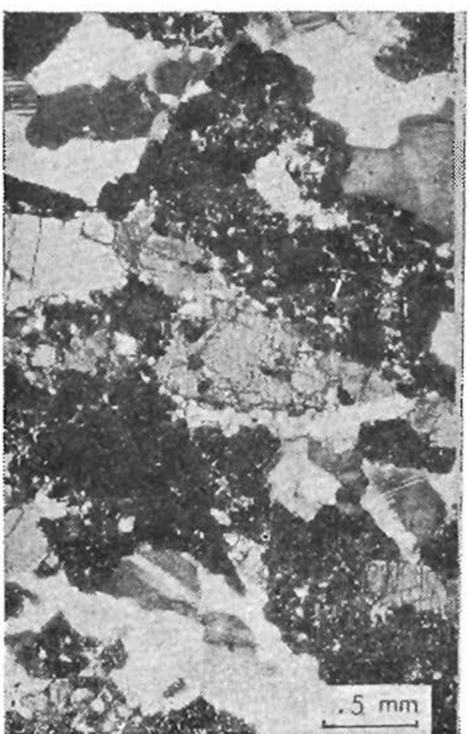

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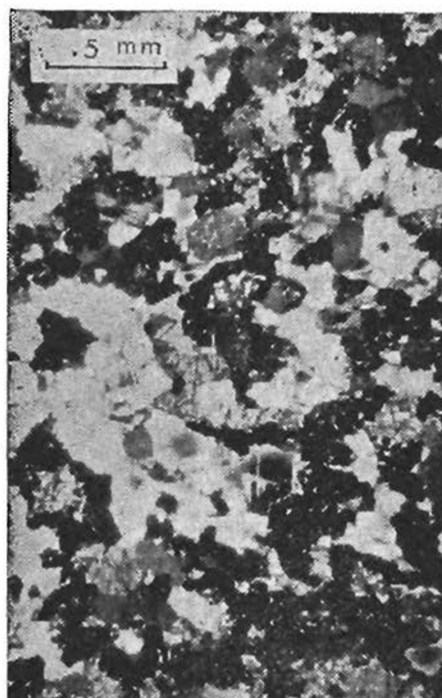

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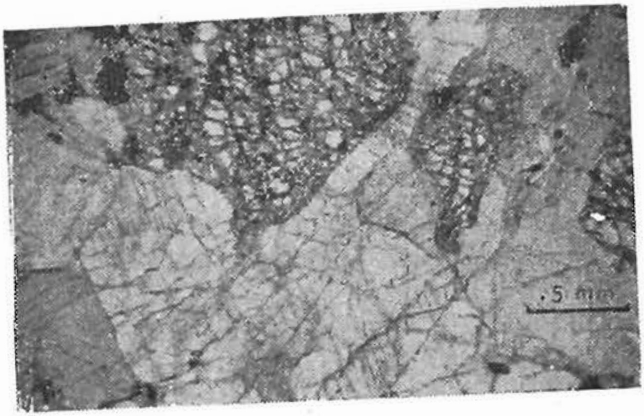

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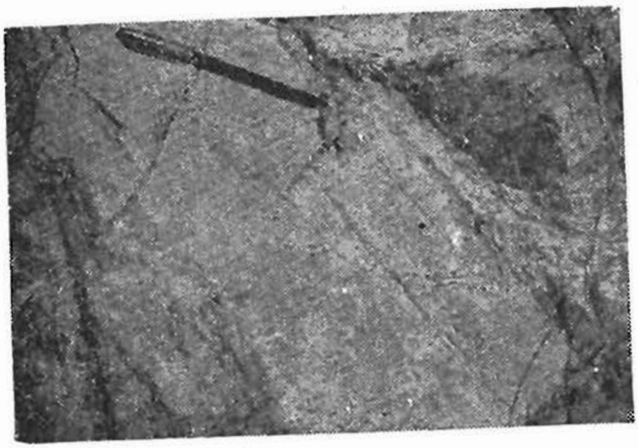

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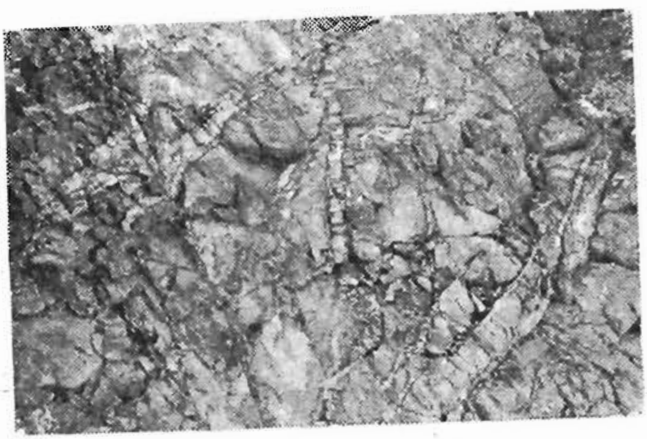

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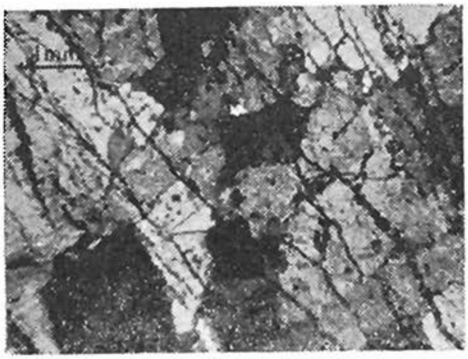

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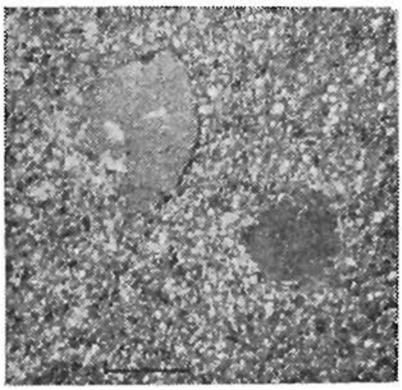

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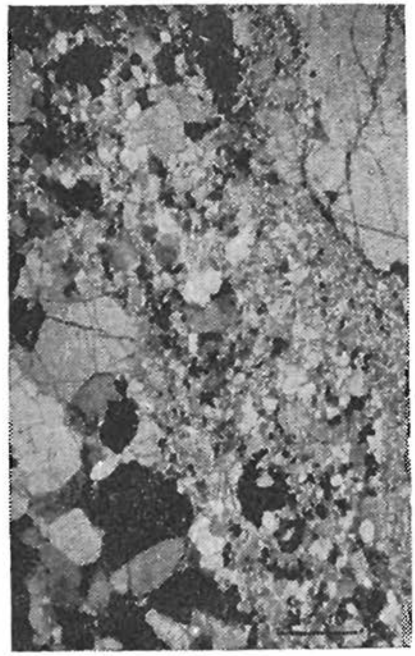

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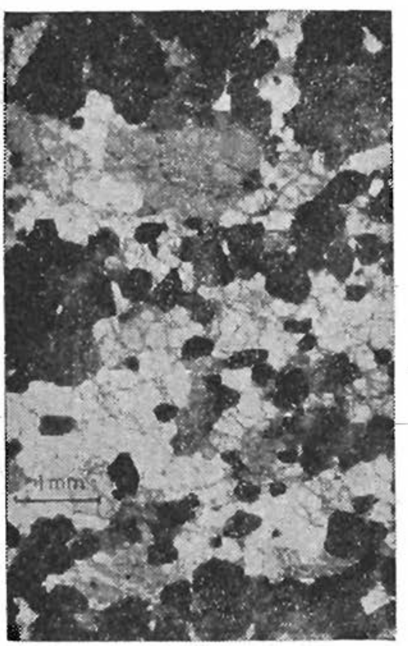

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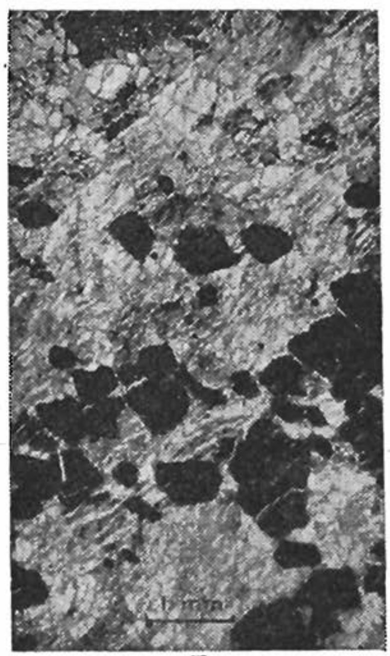

E

PLATE 1

A. Banded granulite in Duber stream. The bands have probably been produced by metamorphic differentiation and attain a pegmatitic aspect in some cases (on the right, for example). The dark patch near the tip of the hammer may be a xenolith.

B. A typical garnet granulite outcrop 2 km S of Patan. Dark xenoliths and mafic and felsic veins are noticeable. One of the veins is studded with garnet prophyroblasts, is folded and has amphibolitised the host rock on its margins. Garnet is particularly abundant in the boulder next to the hammer head.

C. Abnormally coarse-grained, plagioclase-bearing garnet granulite boulder in Duber stream. Garnet coronas (grey) separate dark (?) pyroxene from felsic material.

PLATE 2

A. Plagioclase-bearing garnet granulite (SI 290) with euhedral garnet (altered along fractures to epidote), cloudy plagioclase, clinopyroxene, and strained quartz (top right). The triangular whitish grain in the centre is a secondary epidote with intergrown quartz vermicules.

B. Clinopyroxene garnetite (SI 268) from the southern granulite patches near Jijal. The garnet grains are fractured but fresh; alteration to epidote (white) has taken place only along the grain boundaries. The white patch in the lower right part is a clinopyroxene grain.

C. Plagioclase-bearing granulite (SI 328) having abundant inclusious in garnet. In the centre is a hypersthene grain (fractured and grey). Such hypersthene grains in the rock are invariably isolated from the plagioclase by an 'envelope' of clinopyroxene and/or garnet, suggesting a possible reaction between the two to produce clinopyroxene and garnet due to increase in pressure.

D. Granulite along Patan stream showing abundant inclusions in the garnet, and zoning and twinning (combined albite and pericline) in the plagioclase. Clinopyroxene (grey), ilmenite and rutile (inclusion-free dark areas) and quartz are the other constituents.