The nature and origin of orbicular rocks from near Deshai, Swat Kohistan, Pakistan

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Abstract

Orbicular dioritic–noritic rocks from an area of mixed metemorphic and igneous rocks in Swat Kohistan, northern Pakistan, have been examined petrographically and chemically in order to determine the nature and origin of the orbicular texture. Using textural and compositional sequences it has been possible to relate the apparently different orbs to one another, and obtain a sequence of orb formation. The majority of the orbs comprise a series of distinct layers (shells) surrounding a central zone (core). Plagioclase, clinopyroxene, orthopyroxene and hornblende form the bulk of the shells. The cores have been extensively recrystallized. The development of a 'comb-layered' texture in some orbs and in associated layered rocks is comparable to that commonly described from other occurrences. A dual igneous/metasomatic crystallization history is invoked to explain the features of the orbs in this locality, the oscillatory zoning of the orbicular structure being caused by the alteration of primary minerals, such as pyroxene to amphibole, due to fluctuations in the p_{H_2O} of the magma.

KEYWORDS: orbicular rocks, diorite, norite, Swat Kohistan, Pakistan.

Introduction

THE majority of occurrences of orbicular structures are in rocks of basic to intermediate composition. Debate about their origin has centred on whether they are primary magmatic or metamorphic (Taubeneck and Poldevaart, 1960; Leveson, 1963, 1966, 1973; Moore and Lockwood, 1973*a* and *b*). Other authors (e.g. Van Diver, 1968; Barrière, 1972; and Mutanen, 1974) have shown that orbicular structures were often primarily magmatic in origin, but that they and the associated country rocks have been affected by later metamorphic or metasomatic events or both and may have been overprinted by late-stage mineral recrystallization. Elliston (1984) reviewed the features observed in orbicules and concluded that orbicular granites crystallized from a hydrosilicate system. These hydromagmas contained sufficient water to enable them to behave as gelatinous colloid systems.

The present work provides further evidence of a magmatic (gabbroic) origin for orbicular growth combined with later metasomatic events which have had a considerable effect on the mineralogical and chemical compositions of the orbs and the rocks containing them. A brief account of the occurrence was given by Jan and Mian, 1971.

Location and nature of the orbicular host rocks

The area around Deshai is one of extreme relief on either side of the valley of the Ushu River (Fig. 1). Diorites predominate, with subordinate metasedimentary and granitic rocks; the whole constitutes a part of the over 2500 km long Transhimalayan plutonic belt of Cretaceous–Tertiary age (Jan and Asif, 1983). The metasedimentary rocks are exposed mainly on the western side of the Ushu River, but also occur locally within the diorites to the east. The Ushu valley follows the line of a fault with a sinistral displacement of about 1 km which has resulted in two outcrops of orbicular rocks. The larger, elongated outcrop lies 0.5 km north of Deshai on the eastern side of the river and a

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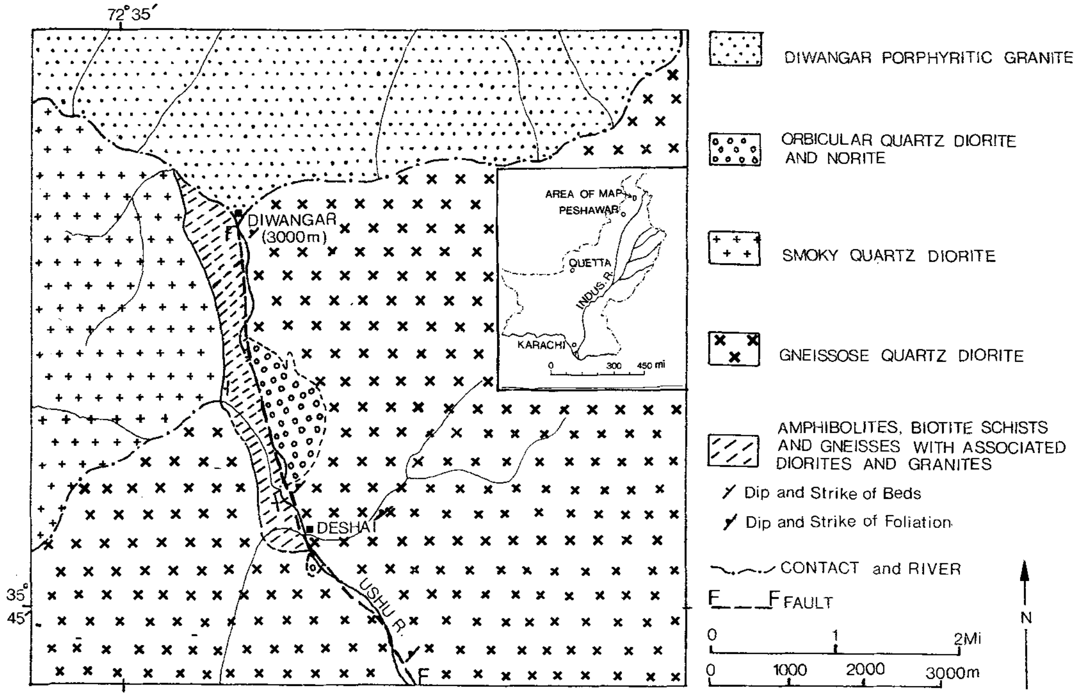

FIG. 1. Geological map of the Deshai–Diwangar area, Swat Kohistan, Pakistan.

much smaller outcrop occurs 0.5 km south of Deshai on the western side of the river. Owing to the relief, the exact position and nature of the eastern contact of the major outcrop of orbicular rocks is not known, and the position of the contact has been mapped on the basis of surface morphology and weathering pattern alone. The orb-bearing (host) rocks are diorites and norites intrusive into gneissose quartz diorites probably of Cretaceous age (Petterson and Windley, 1985).

The orbicular diorites, in which the majority of the orbs occur, are composed of plagioclase, clinopyroxene, hornblende, biotite, quartz and minor ilmenite and/or magnetite, apatite and sphene. Secondary muscovite and epidote also occur. The plagioclase, a zoned andesine–labradorite, locally forms myrmekitic structures with quartz, and is in places clouded by small opaque inclusions. Augite, often uralitized, is dominant over hypersthene and in most sections both minerals have been extensively replaced by hornblende. Both hornblende and biotite are usually poikilitic, and the biotite is frequently altered to chlorite.

The orbicular norites consist of plagioclase feldspar, hypersthene, augite, hornblende, minor biotite, magnetite and ilmenite, with a little quartz and apatite. The plagioclase is usually a zoned labradorite. The hypersthene is commonly extensively altered to colourless uralite, and in most cases the clinopyroxene is partially replaced by hornblende although, overall, pyroxene is dominant over amphibole. Secondary epidote is common in the more altered rocks. Whole-rock analyses of the host rocks are given in Table 1 and compositional variation plots of the major minerals in Fig. 2.

Mode of occurrence of the orbs

The orbs occur as solitary structures randomly distributed throughout the diorite and norite or as closely packed groups principally within the diorite (Fig. 3). The groups are usually less than two metres across but can make up to 80 per cent of the rock mass. Some of the groups are bounded by a zone of alteration or layering similar to that forming the orb shells, a feature similar to that described by Bryhni and Dons (1975) in an orb-bearing dyke from Norway.

Where the orbs are closely packed they are normally separated from each other by a coarser-grained matrix often richer in ferromagnesian minerals (notably amphibole) than either the orbs themselves or the host rocks. In some orbs the cores are also more mafic and usually composed of a

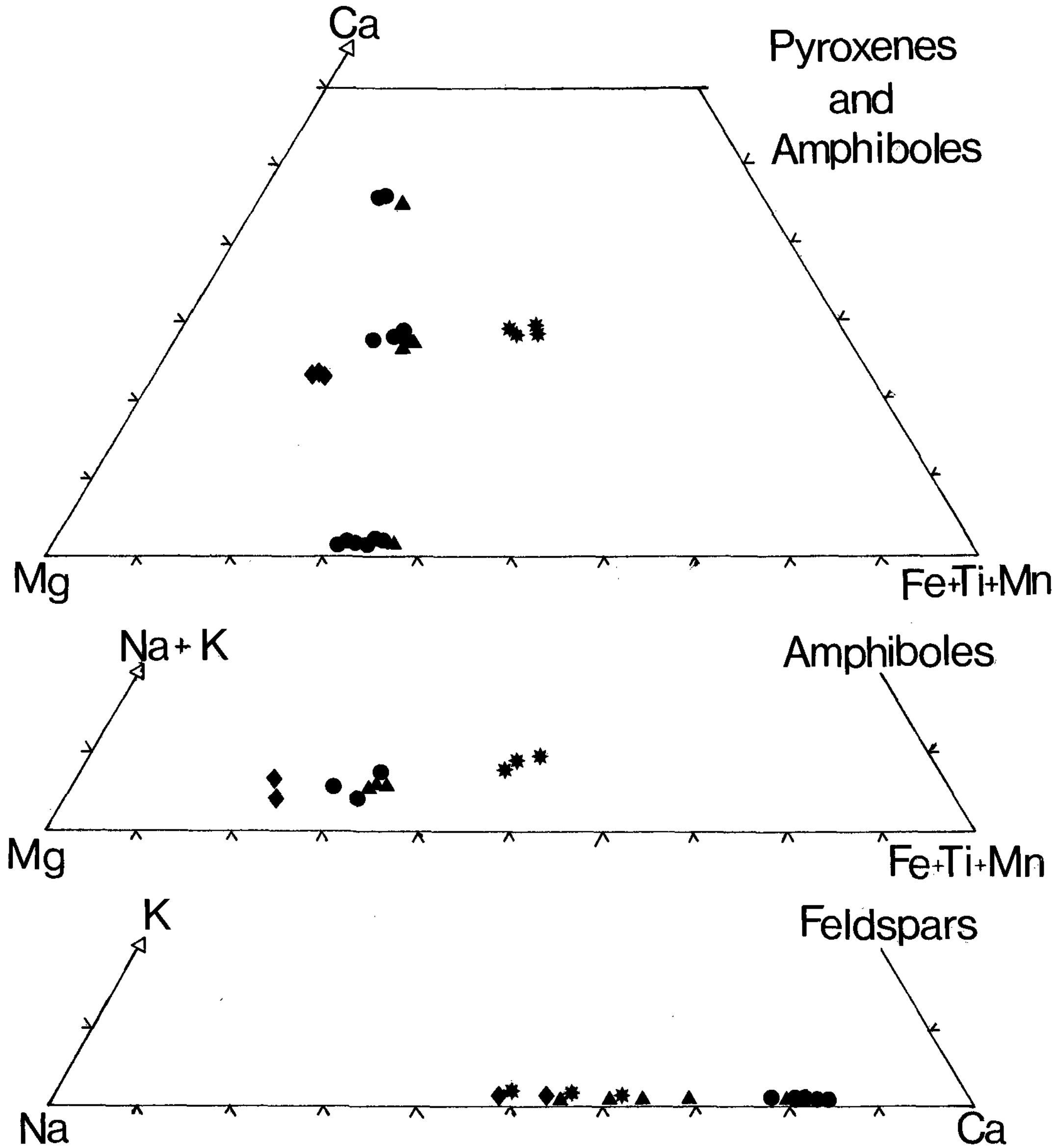

FIG. 2. Compositional variation plots of the major minerals in the rocks associated with orbicular texture. ▲ norite, containing orbicules (D.1); ● layered norite (D.3); ◆ diorite, containing orbicules (D.5); and ★ gneissose quartz diorite (D.7) directly outside the orbicular area.

recrystallized pegmatitic hornblende and biotite assemblage similar to that of the surrounding matrix. In some orb sections, such as orb K (Fig. 4), the secondary amphibole extends from the matrix, through the shells of the orbicular structure, into the core.

Occasionally the orbs are veined by quartz and hornblende, and because dislocation along the veins affects the orb shells but not the surrounding matrix, it is suggested that these minerals crystallized in fractures produced in the orb before the magma had completely solidified. In some instances fragments of orbs have been moved short distances prior to complete crystallization of the matrix, and form the cores of further orb structures. Cognate xenoliths of a hornblende-rich diorite occur within

Table 1. Whole rock analyses

	1	2	3	4	5	6
SiO_2	48.6	47.5	55.5	60.0	51.7	48.0
TiO_2	0.81	0.40	0.77	0.66	0.71	0.43
Al_2O_3	19.8	18.0	18.3	17.5	20.1	15.7
Fe_2O_3	3.9	1.5	2.8	2.2	2.6	1.3
FeO	6.4	8.3	5.0	4.3	5.2	5.7
MnO	0.19	0.19	0.14	0.13	0.12	0.16
MgO	5.7	10.8	4.0	3.2	4.7	9.7
CaO	10.3	11.2	7.8	6.3	11.0	16.5
Na_2O	2.8	1.2	3.0	2.9	1.7	1.1
K_2O	0.23	0.10	1.1	1.8	0.94	0.29
H_2O^+	0.80	0.44	1.2	1.2	0.91	1.0
H_2O^-	0.05	0.05	0.09	0.01	0.05	0.07
P_2O_5	0.17	0.05	0.18	0.17	0.12	0.06
CO_2	0.18	0.28	0.24	0.22	0.33	0.34
TOTAL	99.93	100.01	100.12	100.59	100.18	100.35

Analyst V.K. Din. FeO determined by 'plastic bottle' method (French and Adams, 1972); H_2O^- gravimetric (110°C); H_2O^+/CO_2 by elemental analyser (Din and Jones, 1978); the remainder (including total Fe) XRF analysis of $LiBO_2$ discs.

1. Norite (O.1) containing orbs.
2. Layered norite (O.3).
3. Diorite (O.5) containing orbs.
4. Quartz (O.7) gneissose diorite.
5. 'Diorite' core to orb OM.
6. Comb-layered shells to orb OM.

areas of normal orbicular development. Some of these are spheroidal but they are usually smaller than true orbs and have compositions similar to those of the host rocks.

Rocks with a fine-scale layering also occur. The layers have textural patterns and mineralogical compositions similar to those of the orbs.

Petrography and texture of the orbs

Field observations and laboratory studies of orbs collected from loose blocks show the orbs to be of two types (A and B). Orbs of *type A* (max. diameter 7 cm) are rare and are found only as single, randomly-distributed structures in the norite. They are usually spheroidal, with a more or less central granular core formed from a cluster of olivine and/or pyroxene crystals, as in (orb specimen OA, Fig. 5*a*) surrounded by an indistinct inner shell of radially arranged plagioclase feldspar (bytownite-anorthite) with olivine, hypersthene, hornblende, minor clinopyroxene and accessory ore and apatite. This is followed by a thin, darker, fine-grained outer shell with tangentially arranged crystals. Olivine in both elongated radial and equant grains is often

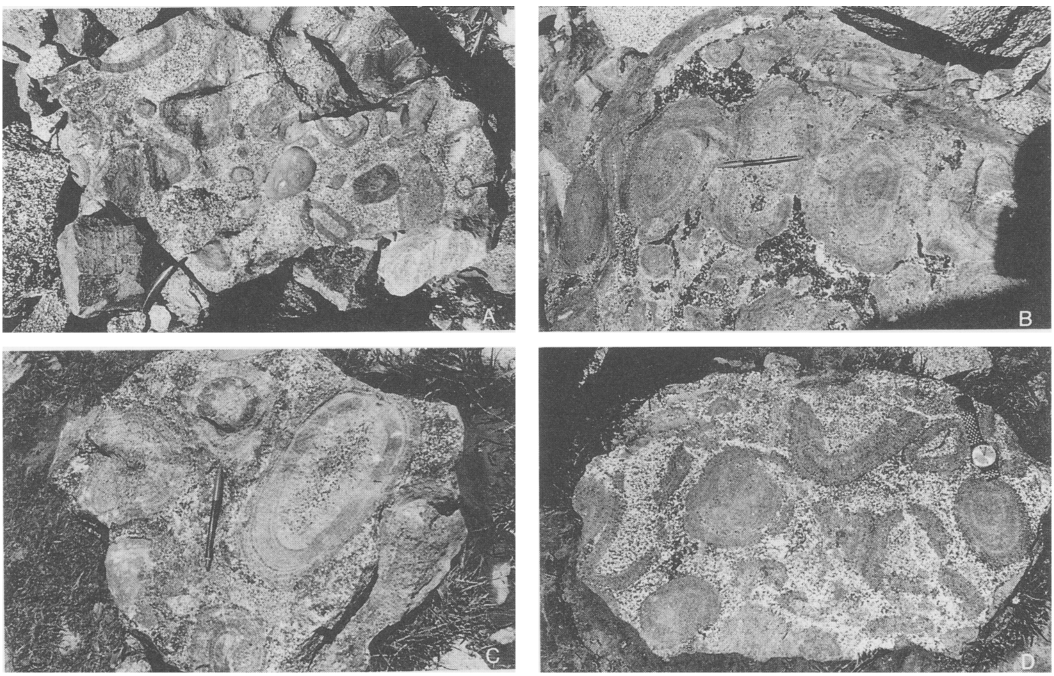

FIG. 3. Dioritic/noritic blocks showing features of the orbicular development: (A) Group of single and multi-shelled orbs, most shells having radial crystal growth; (b) Closely packed orbs, slightly modified by mutual interference, associated with coarse hornblende-rich areas partially replacing the orbicular structure (pen is 9.5 cm); (C) Multi-shelled orbs some with coarse crystalline cores; (D) Group of broken and transported orbs.

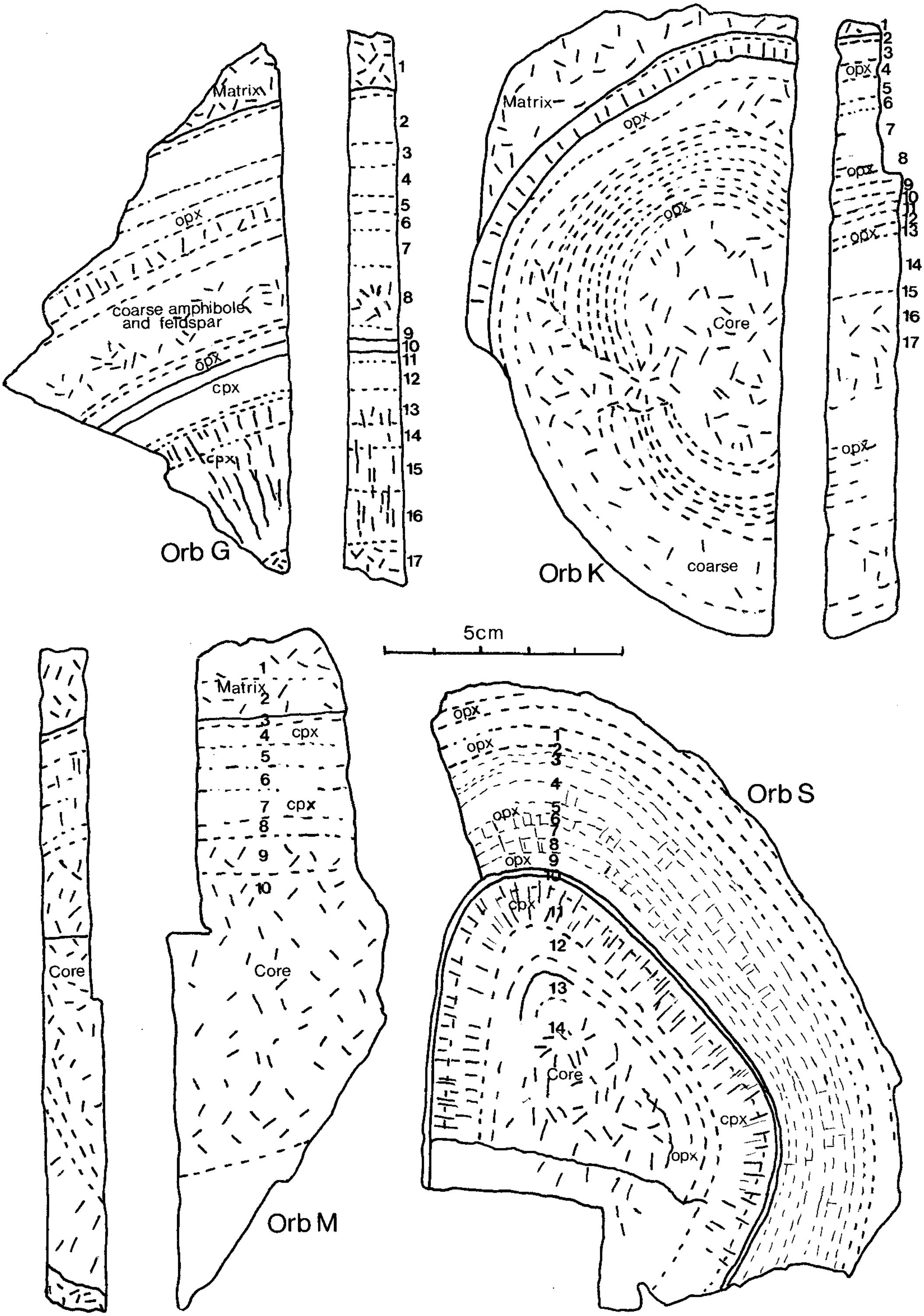

FIG. 4. Sketches of type 'B' orbs, showing the zone sequences analysed.

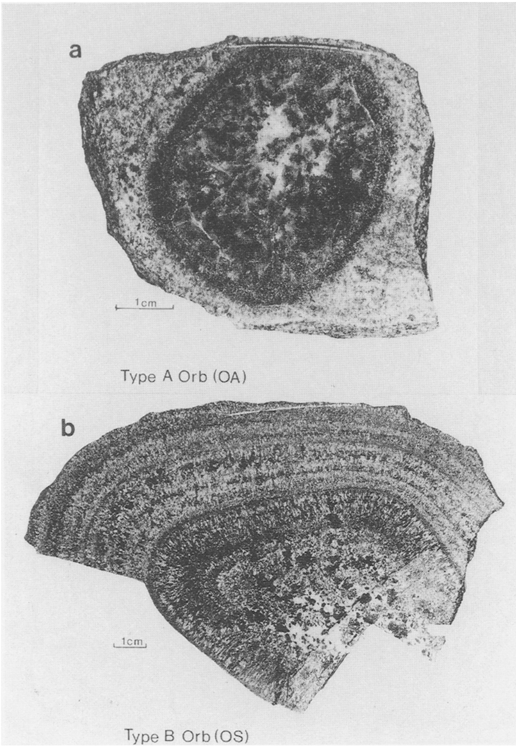

FIG. 5. Examples of types A and B orbs.

rimmed by a corona of colourless hypersthene followed outwards by a light green hornblende, which may be intergrown with a dark green spinel (Table 2). Although the narrow outer shell of the orb has a higher modal content of mafic minerals, especially orthopyroxene, the compositions of both orthopyroxene and olivine in the outer shell are similar to those in the radial shell. Both orthopyroxenes and the associated amphiboles (green hornblende) are more magnesian in the type A orb studied (specimen OA) than in type B, which suggests that type A orbs may have formed at higher temperatures. The higher average An content (An_{93}) of the plagioclase also supports this hypothesis.

Type B orbs are by far the more abundant and are found in both diorite and norite. They are spheroidal to ellipsoidal and are composed of one or more distinct shells surrounding a core (Fig. 5*b*). They range from 2 cm to 35 cm in diameter, averaging about 12 cm, and contain from one to twenty distinct shells.

Original cores are hard to define, either in extent or composition, because of the extensive late recrystallization of hornblende, biotite, quartz and sodic feldspar, but from analysis of remnant pyroxene and plagioclase it appears that the primary mineral compositions of the cores were little different from those of the dioritic and noritic host rocks. Indeed, those orbs with little secondary alteration have pyroxene-rich cores which appear to be cognate xenoliths of the noritic host rocks. Where not overprinted by secondary recrystallization, the boundary between the core and the first shell is relatively sharp, with distinct textural and compositional differences between them.

Table 2. Representative electron microprobe analyses of phases in orb type A (Fig.5)

	1	2	3	4
SiO_2	39.5	54.5	43.3	-
TiO_2	-	-	0.18	-
Al_2O_3	-	2.8	14.3	61.4
FeO^*	20.5	13.4	8.4	20.8
MgO	40.9	28.2	16.0	16.3
CaO	-	0.24	11.3	-
Na_2O	-	-	2.0	-
K_2O	-	-	0.21	-
TOTAL	100.9	99.14	95.69	98.5

Analysis (1) olivine in radial growth zone, rimmed by orthopyroxene (2) and a corona of green hornblendic amphibole (3). The latter is intergrown with a dark green vermicular spinel (4).

Analyst. R.F. Symes. *Total iron shown as FeO

The spacing of the shells is irregular; shell thicknesses range from 0.5 mm to 5 cm (in comb-layered shells) with most being a few millimetres wide and more or less uniform in thickness. The shells show rhythmic variation in colour index, grain size and degree of radial growth; comb-layer (radial) growth is most common in the inner shells, and the outermost shell in most cases is non-radial and fine-grained. Plagioclase feldspar, hornblende, clinopyroxene and orthopyroxene form the bulk of the shells, with rare magnetite, ilmenite and interstitial quartz. Thin sections show that while mafic minerals are usually confined within shell boundaries, plagioclase grains sometimes cross them. All the minerals tend to be anhedral.

Detailed mineralogy of type B orbs

Five type B orbs (G, H, K, M and S) and a specimen of the layered norite (D.3) were examined in polished thin section, both optically and by electron microprobe. From the data on mineral

Table 3. Composite crystallization sequence for type B orbs

Dominant mineral	Texture	Pyroxene composition Fe atom %	Amphibole composition Fe atom %	Plagioclase composition An %	Range of orb shells
MATRIX	coarse grained amphibole and plagioclase (some primary plagioclase remnants)		(26.2-32.5)	82.7 (57.6-65.4)	OrbG
ORB SHELLS					
plagioclase	med-fine granular	-	-	85.1	
amphibole	mostly recryst.	-	(32.0)	79.5	
amphibole	mostly recryst.	-	(29.0)	82.0	OrbK
opx + amph	narrow zone granular	30.9	25.0	84.2	
opx + amph	comb layer some recryst.	34.1	26.4	77.8	
opx		31.1	-	85.6	
amph (+ opx)		-	19.1	83.9	
opx		32.6	23.9	84.5	
amphibole	strongly recryst.	-	(28.3)	82.8	
opx		29.7	-	86.9	
amp (+ opx)		-	20.7	-	
opx		29.0	-	88.3	
amph (+ opx)	repeated units	-	22.6	86.9	
opx		28.7	-	-	OrbS
amph (+ opx)	comb and granular crystals	-	21.0	-	
opx		24.7	-	92.7	
amph (+ opx)		-	19.3	-	2nd Series
opx		25.3	-	93.5	
amph (+ opx)		-	19.0	91.0	
opx		29.3	-	-	
amph (+ opx)		-	20.1	89.3	
opx		29.8	-	87.7	
amph (+ opx)		-	20.3	82.3	
opx		28.7	-	82.2	
amph (+ opx)		-	19.4	91.4	
opx		30.0	-	91.5	
amph (+ opx)		-	23.7	-	not
opx		32.8	-	86.2	represented
amph (+ opx)	coarse recryst.	-	24.3(28.5)	-	
opx		33.8	-	86.1	
amphibole	narrow zone granular	-	23.2	88.8	Core
......sharp boundary......					
amphibole	fine-grained	-	22.8	86.6	
plagioclase feldspar					
......sharp boundary......					
cpx + amph		11.7	20.8	83.7	
cpx + amph		12.3	20.4	83.8	OrbH
amph	comb	-	21.7	82.2	
cpx + amph		12.4	22.3	79.4	OrbM
cpx + amph	one crystal layering	11.4	22.2	80.2	1st Series
cpx + amph		12.4	23.2	84.2	
cpx + amph		12.3	23.6	82.0	
cpx + amph		12.5	24.1	83.6	Core
opx + amph	some recryst.	34.7	22.6	(52.6)	
		-	(28.7)	79.4	
CORE	mostly recrystallised coarse grained amphibole/plagioclase (some primary pyroxene and plagioclase remnants)	-	22.9 (28.4-32.0)	79.4 (52.7-67.5)	

Table 3 has been compiled using the highest reproducible values for Fs and An in the limited range obtained for each shell. Pyroxene compositions (Fs) are Fe atomic % relative to Fe, Mg and Ca; amphibole compositions are Fe atomic % relative to [Fe+Ti+Mn], Mg and Ca; and plagioclase compositions are given as An %. Where secondary recrystallization is important representative analyses are shown in brackets.

The analyses are predominantly wavelength-dispersive electron probe microanalyses obtained using a Cambridge Instruments Geoscan; further collaborative analyses were made using Link Systems energy dispersive equipment attached to a Geoscan microanalyser. Analysts J.C. Bevan and R.F. Symes.

composition and textural type it was possible to correlate apparently different orbs using characteristic shell sequences, and to construct a composite crystallization model for the type B orbicular structures (Table 3). A similar model was made for the layered norite (Table 4).

In the most complete orbs, the earliest shells are orthopyroxene-bearing (Table 3). Next is a zone of comb-layering (see shells 13–16 of orb G, Fig. 4) where clinopyroxene forms the main structural framework. Individual comb crystals are up to 1 cm long and branch outwards in the direction of growth. They are now partially replaced by amphibole, which forms a broad rim around a narrow remnant core of pyroxene, both phases changing composition gradually from one end to the other in accordance with the observed cryptic variation in the shell sequence. This variation has an outward trend towards Fe depletion (Table 3). Plagioclase crystals have a similar radial zonation either along their length or from the core to rim.

A major change in deposition can be inferred from the presence in some orbs of a thin shell following the clinopyroxene comb-layering (e.g. zone 10 of orbs G and S, Fig. 4). This shell is composed of fine-grained granular amphibole and plagioclase with no trace of pyroxene: it marks the boundary between the first orthopyroxene–clinopyroxene series and a second. The chemical composition of the pyroxene in the first shell of the second series is close to that of the pyroxene in the first shell of the first series, implying a return to the physico-chemical conditions under which the orbs began to form.

Further shells are composed of units containing pinkish-brown orthopyroxene alternating with others containing dark green amphibole, with plagioclase always present (see zones 6–13 of orb K, for example, Fig. 4). However, in the amphibole-rich zones, relict cores of orthopyroxene in amphibole are common. This second zonal sequence has at first a reversed orthopyroxene compositional trend (usually mirrored by the coexisting amphibole) towards Fe depletion but changes (with no apparent break in deposition) to a normal Fe enrichment trend for the rest of the sequence (Table 3). In these later zones, comb-layered, orthopyroxene-rich shells may be present; crystals are much smaller than those of the clinopyroxene comb-layering and the shell thickness is much reduced. Plagioclase feldspar remains relatively unaltered.

The primary amphibole of the orbicular shells appears to be the result of magma reaction with

Table 4. Crystallization sequence for part of layered norite (D.3)

Dominant mineral	Texture	Pyroxene composition Fe atom %	Amphibole composition Fe atom %	Plagioclase composition Ca atom % An %
amph (+ opx)	coarse comb layering	32.5	22.4	78.5
amph (+ opx)	fine comb layering	34.2	24.1	81.1
plagioclase feldspar (95% modal)	fine granular	34.0	-	81.3-84.5
amph (+ opx)	coarse comb layering	33.1	23.1	81.1
{ amph (+ opx) / opx / plagioclase feldspar	*oscillatory crystallization (3 units)*	32.4	23.8	82.5
at base amph (+ opx)		34.9	21.1	-
plagioclase feldspar (95% modal)	fine granular	-	-	82.1
{ amph (+ opx) / opx	*oscillatory crystallization (3 units)*	33.8	24.0	81.2
plagioclase feldspar		33.4	-	83.0
amph, opx and cpx	coarse comb or columnar layering	11.9 (cpx) 33.0 (opx)	23.5	83.6
plagioclase feldspar (95% modal), opx	fine granular	32.6	-	81.2
amph (+ opx)	comb and granular layering	33.1	24.8	79.6

Analytical values have been determined by EPMA and compiled according to the scheme described for Table 3. Analysts R.F. Symes and J.C. Bevan.

ortho- or clinopyroxene: its composition is directly related to that of the parent pyroxene. In contrast, the later secondary amphibole which overprints much of the shell sequence is richer in Fe, Ti and usually Na and K (see Fig. 6) and is strongly zoned. Recrystallization and replacement of orb shells by this Fe, Ti-rich amphibole and sodic plagioclase has preferentially affected the orthopyroxene-bearing shells and cores, sometimes following a single shell (orb G, Fig. 4) and in extreme cases leaving only a broad clinopyroxene comb-layered shell (as in orb M, Fig. 4).

The layered norite

Within the noritic rocks showing development of orbs, there are localized occurrences of distinctive layered rocks. The textural and mineralogical sequence for a small specimen (D.3) of this layered sequence is shown in Table 4. It is similar to that shown for the type B orbs, in that the compositions of orthopyroxene, clinopyroxene and associated calcic plagioclase fall within the same range. Amphibole, where developed, again replaces primary clino- or orthopyroxene and its composition is related to that of the replaced mineral. Both fine-grained, granular and 'comb' layers are present. The sequence is essentially one of an orthopyroxene layer of various textural types followed by alternating layers of orthopyroxene with amphibole and plagioclase. Plagioclase is generally fresh and unsericitised and thin, granular leucocratic layers containing modal plagioclase up to 95%, similar to some in the type B orbs, may separate comb layers.

Discussion of orb formation

Orbicular occurrences are usually developed at the margins of plutons, mostly of basic to intermediate bulk composition. Taubeneck and Poldervaart (1960) described the igneous layering associated with a small intrusion on the southern edge of the Bald Mountain tonalite batholith of the western U.S.A. This small funnel-shaped intrusion is essentially basic in composition, consisting of metagabbros and norites, and contains layering of a type the authors called 'Willow Lake'. This consists of a profusion of very thin (7 mm or less) layers, some of which are composed of minerals with their long axes perpendicular or sub-perpendicular to the plane of the layering. Plagioclase, hornblende, orthopyroxene and clinopyroxene are common. The authors also drew attention to the markedly similar rhythmic layering that had developed around xenoliths (orbicular growth) in the same intrusive complex. They explained the rhythmic character of this layering as resulting from undercooling near the margins of the intrusion, followed by a slight rise in temperature due to the release of latent heat of crystallization, and then continued undercooling. This process accounts for the many alternating layers of contrasting mineralogy and for the elongate branching forms of the crystals which were able to grow rapidly into the undercooled melt from the surface of the preceding layer. Moore and Lockwood (1973*a*) discussed the origin of some Willow Lake layering and orbicular structures from the Sierra Nevada batholith. They proposed the term 'comb-layering' to replace the term 'Willow Lake' layering of Poldervaart and Taubeneck.

Comb-layering, often described in earlier literature as 'radial growth', is common in orbicular structures and their associated wall-rock crystallization. This type of growth occurs chiefly at or near contacts, along walls or dykes, or on overhanging walls of plutons. Moore and Lockwood suggested, from field evidence, that the comb-layering on wall rock and as orbicular development around xenoliths was the result of the upward migration of large volumes of aqueous fluid along contacts between magma and wall rock, or along an interface between magma and previously solidified melt, the best-developed comb-layering and orb formation being largely restricted to structural traps.

Leveson (1973), however, considered it equally valid that the type of layering described by Moore and Lockwood should be developed through metamorphic recrystallization or replacement and that the formation of these features was sequential to, rather than simultaneous with, magmatic activity, and was possibly due to a static metasomatic process under conditions of active diffusion in a water-rich, high-temperature metamorphic environment.

Late magmatic aqueous fluids certainly have an important effect on the final orbicular rock, but recently it has been shown (see below) that synmagmatic processes involving aqueous fluids are essential for the production of the characteristic alternating shell pattern of the orbs.

Van Diver and Maggetti (1975) and Maggetti *et al.* (1978) described an orbicular gabbro from Reichenbach in West Germany. The rocks sampled were loose blocks of orbicular gabbro and layered gabbros which could be directly related to certain areas of the associated parent intrusion. There, the orb shells are virtually identical in mineralogy, texture and structure to the associated comb-layered gabbroic rocks. The orb shells are generally either dark, with a fine-grained directionless texture, or light, with comb-layered plagioclase feldspar. The authors considered that the orbs formed near

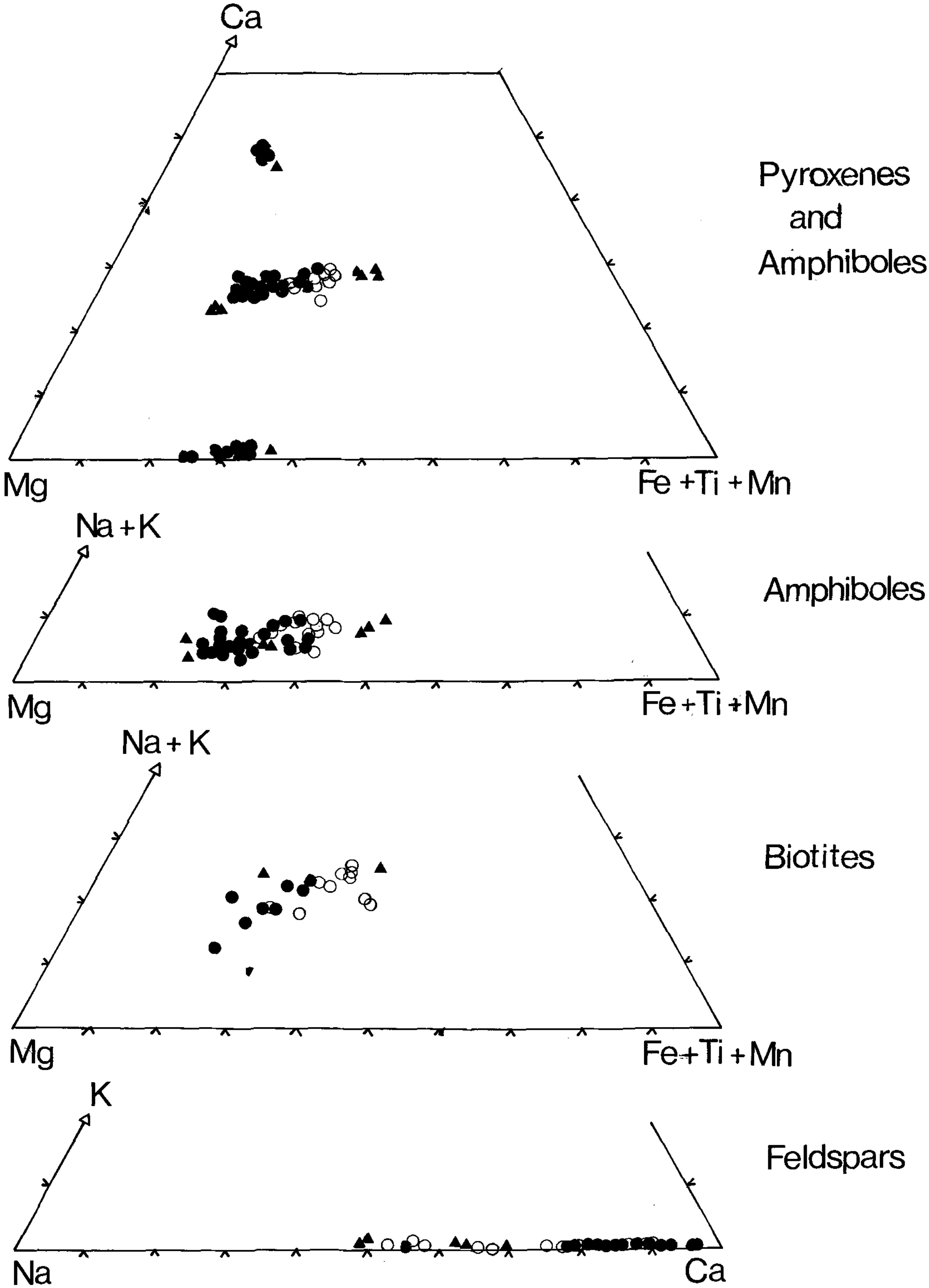

FIG. 6. Compositional variation plots of the major minerals in the type 'B' orbicular rocks. ● primary minerals, mostly in shells (including syn-magmatic amphiboles and biotites); ○ secondary minerals in areas of recrystallization, mostly in cores; ▲ country rocks (see Fig. 2).

to contacts during the normal crystallization of the magma and that the texture of each shell varied from normal gabbroic to comb-layered according to the degree of undercooling. The periodicity of the shell formation results from fluctuations in p_{H_2O}, by alternate containment and release of volatile components, so that a pattern of crystal encrustation, hydrothermal alteration of the last-formed shell, and further encrustation occurred. The comb layers themselves are often largely obscured by a later decussate blanket of sericite and actinolite, although other layers may be almost completely unaltered.

Although it is believed here that metamorphic and metasomatic processes alone can form some types of orb development, and that late-stage metamorphic and metasomatic processes do commonly affect gabbro/diorite orbicular rocks, it is hard to explain the presence of broken, mutually distorted and transported layered and orbicular material other than by proposing a magmatic origin. In many of the described gabbroic–dioritic orbicular occurrences, textural and compositional characteristics of the primary mineral phases also point to a magmatic origin.

Discussion of the Deshai, Pakistan, orbs

Type A orbs are early-formed, high-temperature olivine- and plagioclase-rich, and characterized by radiating crystal form. They occur only in the noritic rocks and probably formed in a supercooled gabbroic magma containing very few nuclei so that rapid growth at isolated sites could occur. An outer mafic shell of granular, fine-grained material marks a slowing of this rapid growth. Olivine has undergone reaction with surrounding plagioclase to give spinel-bearing corona structures similar to those in troctolites from the Chilas complex (Jan *et al.*, 1984) and due either to metamorphic processes or to the action of magmatic residua at high temperature (Gardner and Robins, 1973). They have not suffered the extensive late-stage recrystallization which has affected the type B orbs.

In the most complete sequences the formation of the type B orbs began by the nucleation of orthopyroxene and plagioclase feldspar at growth points on the surface of a xenolith, cognate or otherwise. These xenoliths had been transported into the area of orb development, probably along magma channels, at a late stage in the crystallization of the gabbroic magma. The xenoliths acted as sites for crystal nucleation within a localized regime of under-cooled magma. Crystallization of orthopyroxene proceeded until changing pressure–temperature conditions made clinopyroxene the stable mafic phase. Where this stage of orb growth is seen, clinopyroxene invariably takes the form of fine, branching, comb-layered crystals, indicative of rapid growth in a fluid-rich environment (Lofgren and Donaldson, 1975). The very slight trend in iron depletion (see Table 3) could be due either to the rapidly-growing orb sinking slowly in the magma channel to a zone of higher temperature, or perhaps to rapid crystal growth depleting the immediate magma in iron. The lack of zoning in the neighbouring comb-layered crystals of plagioclase (around An_{83}) favours the latter hypothesis.

After this stage, a change in the physico-chemical environment occurred, as evinced by a sharp outer boundary to the comb-layered shell and the formation of a thin shell of granular, fine-grained amphibole and plagioclase. This change may have been caused by a large influx of magma close in composition and temperature to that of the initial magma at the onset of crystallization. Certainly the orthopyroxene composition (Fs_{34}) is similar to that in the first-formed shells. Crystallization of orthopyroxene and plagioclase continued, with a return to radially-arranged crystals of both minerals within the shells. Initially, the cryptic variation in orthopyroxene composition is again reversed (Fs_{34} to Fs_{25}), but at Fs_{25} the sequence switches to a normal one of Fe enrichment. This variation could be due to changes in the temperature regime within a magma channel.

Throughout the crystallization history of the orbs, oscillations, either local or large-scale, in the p_{H_2O} of the magma probably occurred and account for the rhythmic variation in the proportion of amphibole in each shell; this is responsible for the striking multi-shelled appearance of these structures. The orthopyroxene series is overprinted by a rhythmic alteration of pyroxene to an amphibole which is related in composition to, and encloses relict cores of, the parent pyroxene (Table 3). This alteration seems likely to have been almost contemporaneous with the primary crystallization, since selective attack by later fluids on the solid orb to this extent (up to twelve pairs of continuous, narrow shells are observed) is extremely unlikely. Each pair of shells represents an original orthopyroxene shell, the outer part of which has been altered to amphibole by reaction with the magma. The sharp shell boundaries are due, not to textural differences, but to secondary amphibole formation. The early clinopyroxene-rich comb-layered shells show similar partial alteration of pyroxene to amphibole. Regular, rhythmic increase and decrease in p_{H_2O} of the type postulated may have been due to local water-enrichment of an already hydrous magma during the crystallization of orthopyroxene. Alteration of pyroxene to amphibole then followed, dehydrating the magma around the orb sufficiently for anhydrous phases to begin to crystallize again. The water may have derived originally from xenoliths or from adjacent wall rock, hence the characteristic occurrence of orb-bearing rocks close to an intrusive contact. However, this hydration had little effect on the plagioclase, which remains remarkably fresh.

A second alteration phase, of late-stage metasomatic replacement and generally confined to the area of orbicular development, has affected all the type B orbs studied and their immediate host rocks to a greater or lesser extent. All the cores of these orbs have suffered some recrystallization, so that original mineralogy and textures are rarely seen. Fig. 4 shows how this partial recrystallization has affected the orbs. The coarse amphibole–sodic-plagioclase replacement can be seen to follow an outer shell (Fig. 4), transgress shells, and cross-cut as a neck of recrystallized material from the outer zones to the core through ten or more shells (Fig. 4). The mineral chemistry of these recrystallized zones confirms their secondary nature. Primary plagioclase is invariably close to An_{80} in composition, consistent with the Mg-rich clino- and orthopyroxene compositions. Even the cores of the plagioclase crystals in the secondary coarse-grained areas, however, are normally much more sodic than this, with compositions ranging to An_{60} and below (Fig. 5), lower than any of the rim compositions where zoning was observed in the primary shells. Synmagmatic amphibole is invariably related in composition to the pyroxene it replaces, which is often still present as relict cores. In these amphiboles concentrations of Na, K, Fe and Ti are low. The large secondary amphiboles, however, tend to be richer in these elements. Biotite also occurs in the later alteration zones and from textural evidence seems to have formed at the expense of amphibole. Ca has also been redistributed appearing in prehnite, which occurs as lenses between, and characteristically distorting some of the biotite cleavage plates.

Conclusions

A dual igneous/metasomatic history is invoked to explain all the features of the orbs in this locality. It is believed that the crystals of the comb layers and other shells formed during a magmatic stage but that a later metamorphic/metasomatic event caused considerable recrystallization of the primary mineralogy.

Study of the phase chemistry and textures of the orbs shows that they and the layered norite (probable wall-rock crystallization) may well have formed under essentially the same conditions. Even those appearing in cross-sections as an annulus are probably the result of almost complete replacement and recrystallization of the orthopyroxene-bearing shells, leaving the more resistant clinopyroxene comb-layered shell surrounded by coarse-grained material. Compositions of the clinopyroxene in 'single-shelled' orbs of this type agree with those found in more complete units where the coarse clinopyroxene layers can still be seen to be only part of a complex sequence. The differing structures within the orbicular rocks may relate to the cores having been brought into the environment of orbicular growth over a period of time, so that the latest arrivals show little orb development. Orbs may have developed different thicknesses of corresponding shells, or have interrupted or incomplete crystallization sequences, due to the environment in which they formed, but all of those studied can be related to the crystallization sequence given in Table 3.

Deformation of the orbs occurred both during and after their crystallization and alteration, but usually while the concentric meshes of crystals were sufficiently flexible to distort rather than to fracture. Some break-up of orbs can be seen, with relative displacement of the fragments having occurred under plastic conditions.

The development of orbs in these rocks seems to have been closely similar to that proposed for other occurrences, and resulted from the crystallization from a basic magma of high-temperature plagioclase and pyroxene on xenolith surfaces. Pyroxene has been altered because of fluctuations in the p_{H_2O} of the magma. The primary textural variation between shells, especially that due to growth of comb layers, may be due to the intensity of undercooling (Maggetti *et al.*, 1978). Comb layers form upon a suitable substrate, such as a xenolith, within a magma when the degree of cooling of the magma has a value at which the rate of homogeneous nucleation is low (Donaldson, 1977). The oscillatory zoning in the orbicular structure caused by the alteration of primary minerals, such as pyroxene to amphibole, is not confined to the Pakistan rocks, nor is the late-stage recrystallization which has led to a distinctive amphibole and feldspar mineralogy. However, the relative freshness of the rocks from this locality has facilitated the study of relationships between apparently different types of orb and to the proposal of a composite model for their formation.

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