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AN ORBICULAR TONALITE FROM CALDERA, CHILE

by

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(with 14 text-figures and 3 tables)

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Abstract

First known orbicular outcrop from Chile is described. The body, of Jurassic age, is dyke-like with an exposed surface area of approximately 375 m² and is enclosed in a tonalitic batholith. Both country rock and orbicular body are cut by diabasic dykes. In one locality the contact between country rock and orbicular body is characterized by a zone of comb layering.

The orbicular body has a granodiorite, porphyritic matrix. The surface ratio of matrix/orbicules is 35/65; orbicules are mainly ellipsoidal with an average axis of 7.0 cm and are composed of a quartz diorite core and a single dark shell with a predominantly radial texture composed of equal amounts of plagioclase and amphibole accompanied by lesser amounts of clinopyroxene, biotite and magnetite. Based on texture and distribution of the constituent minerals six zones have been distinguished in the shell. Non-orbicular inclusions in the orbicular body are scarce.

There is a close petrographic similarity between the core of the orbicules, the non-orbicular inclusions and country rock.

Major oxide and selected trace elements are presented and comparisons are made for different rock types.

The petrogenesis of the orbicular body is explained based on two assumptions: a) Non-orbicular inclusions in the orbicular body and the core of orbicules correspond to country rock xenoliths and, b) The shell of the orbicules and the matrix were generated from a same magma during differentiation. A composition for this magma was calculated. Mineralogical and textural features of the shell are explained by a process of alternating supersaturation that induced crystallization of the saturated phase or cotectic crystallization of two main phases. The matrix would correspond to the final fraction of this magma and was formed at the stage when high oxidation ratio and enrichment in SiO₂ and K₂O inhibited the orbicule growing.

Introduction

A coastal dyke-like body of orbicular tonalite crops out approximately 7 km north of Caldera at 27°S latitude. (Fig. 1). The orbicular body is enclosed

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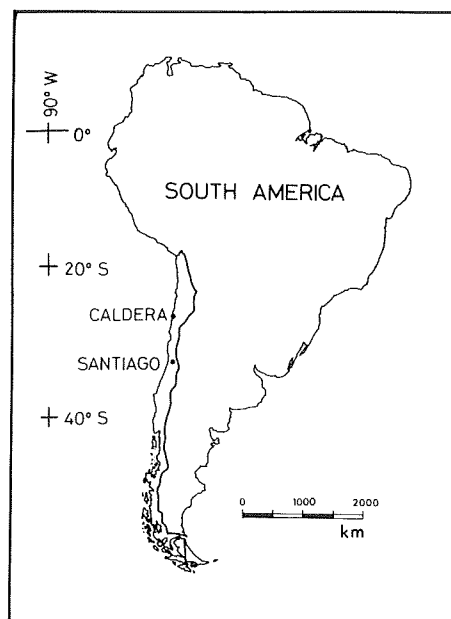


Fig. 1 Location of Caldera, Chile

in a batholith of predominant tonalitic composition of Jurassic age that extends for some tens of kilometers around the studied locality.

The orbicular rock is until now the only outcrop of this type known in Chile and was found in 1961 by F. Ortiz, a geologist from Chile's Instituto de Investigaciones Geológicas. Boulders of orbicular rocks from unknown sources have been collected on the shore at Curauma Point ($33^{\circ}5' S$ latitude) and Tanumé ($34^{\circ}15' S$ latitude); they are probably derived from the Palaeozoic Crystalline Basement that crops out in that coastal region.

According to Snelling (in Farrar and others, 1970) K/Ar ages obtained on hornblende and biotite from a sample of the Caldera orbicular rock were of 182 ± 6 my for the hornblende and 159 ± 5 my for the biotite contained within the orbs.

This paper presents data on field relations, megascopic and microscopic descriptions and chemical analyses of the different rock units. Detailed study of the mineral phases is not intended in this stage and it will be the subject of a future research.

Field Relations

The orbicular body is dyke-like. Along the shore line, in the intertidal zone, the dyke is 15 m thick and can be followed for approximately 25 m inland



Fig. 2 Outcrop of the Caldera orbicular body in the vicinity of Contact 2, intertidal zone.

before it is covered by beach deposits. The total exposure amounts to approximately 375 m². The outcrop has been eroded to a rounded, polished surface making sampling difficult. No loose orbicules are found (Fig. 2).

Contacts between the orbicular body and the country rock are observed in two places; they will be referred to as Contact 1 and Contact 2.

Contact 1 is that located farther inland and is marked by the presence of a sinuous band of the comb layering type (Moore and Lockwood, 1973) with an average thickness of 4 cm (Fig. 3). This band is composed of an alternation of dark and light layers ranging from 1 to 3 mm thick, in which crystals are oriented nearly perpendicular to the layering planes. Twelve to fifteen of these layers can be observed. The layer adjacent to the orbicular rock is darker and thicker than the rest and ranges from 0.5 to 1.0 cm thick. The contact of the comb layering band with the country rock is less sharply defined and is also marked by a dark but rather discontinuous layer.

No orbicules have been truncated by the contact; in rare instances the orbicules are flattened against the contact. In a few cases the orbicules closest to the contact are invaded by small pegmatitic veinlets (Fig. 3, upper central part of figure).

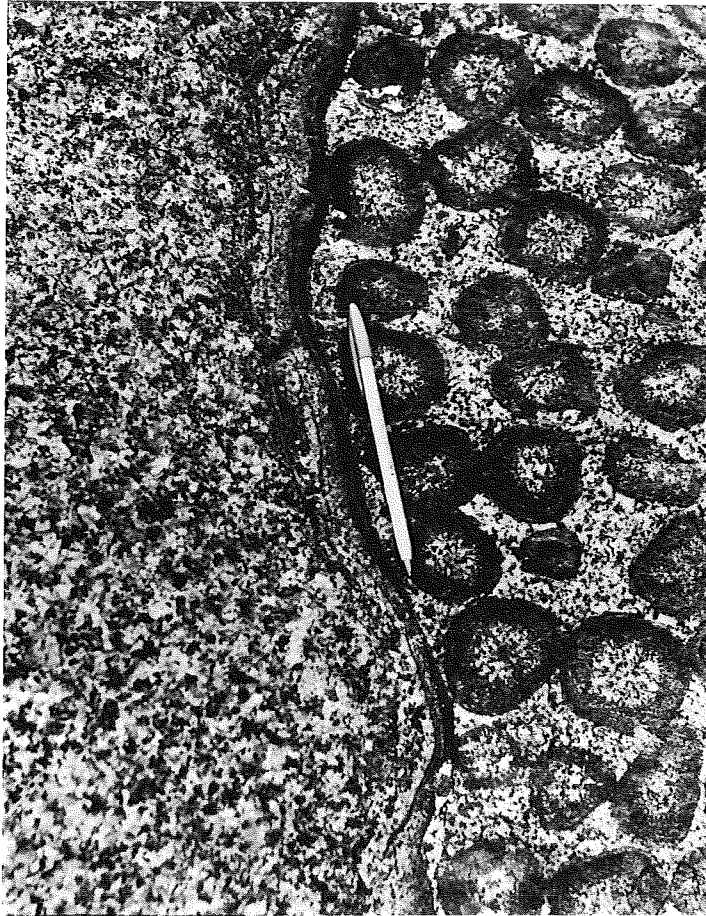


Fig. 3 Contact between the orbicular body and the country rock, Contact 1, marked by the presence of a comb layering band. Note K-feldspar phenocrysts present among orbicules.

The country rock at Contact 1 is a light coloured, medium to coarse-grained, strongly altered granodiorite. Light bleached bands are observed parallel to narrow linear fractures filled by epidote. The predominant direction of these fractures is $N75^{\circ} - N80^{\circ}W$ which approximately coincides with the E-W trend of the contact in part of the outcrop.

Contact 2 is located at the intertidal zone and is also sinous but a multiple layer band is not present. Only a single narrow dark layer of a few millimeters is observed directly in contact with the orbicular rock. As in Contact 1, no truncated orbicules are observed. The country rock here is a medium to dark gray, medium – grained quartz diorite very different in aspect from that of the

country rock at Contact 1.

The orbicular body and the country rock are cut by several microgranular dark diabasic dykes. The dykes range in thickness from 0.8 m to 1.0 cm and sharply cut-across the orbicules. Orbicules are spheroidal to ellipsoidal in shape with an average size of 7 cm; only in a few cases they exhibit a more irregular configuration. They have a core and a shell, the latter made of a broad dark layer of radially oriented minerals. Orbicules are uniformly and densely distributed; they represent 65 percent of the total rock as measured on the surface of the outcrop. Counting done on one square meter of the outcrop yielded 262 orbicules.

Very few disseminated non-orbicular inclusions are found within the orbicular rock. Among them, the most conspicuous is an ellipsoidal (35 cm × 28 cm) boulder of granodiorite around which no shell is developed except for a dark, narrow outer envelope of biotite.

Petrography of the country rock

Observations and sampling of the country rock were made in the immediate vicinity of the orbicular body as well as farther north and south of it.

North and south of the orbicular outcrop, a reconnaissance up to a distance of approximately 0.5 km shows that the country rock is a medium gray, medium-grained tonalite containing plagioclase, quartz, biotite and amphibole. This rock is poor in inclusions; only some scattered, dark diabasic fragments with a maximum size of 20 cm have been observed. Leucocratic aplite and pegmatite dykes and veins are scarce and have an average thickness of 5–10 cm and trend between N55 – N70°W. Melanocratic dykes are more abundant and commonly vary from 2 to 5 m in thickness. They are mainly porphyritic diabase with a dark gray micro-granular groundmass in which phenocrysts of plagioclase with an average size of 2–3 mm are regularly distributed. The strike of the dykes varies from N-S to N28°W. In some places they cut-across aplitic veins.

The tonalite is allotriomorphic to hypidiomorphic granular in texture with an average crystal size of 2–3 mm. Quartz is anhedral and mainly fills intercrystal areas; it has weak wavy extinction and is partly sagenitic. Plagioclase composition varies from An_{48} to An_{52} , in several cases individuals are normally or oscillatory zoned. Some plagioclase crystals are poikilitic in that they enclose small crystals of amphibole. The amphibole is a brownish-green hornblende that is mainly a replacement product of pyroxene as shown by remnant cores of clinopyroxene. In turn, the hornblende has been partly replaced by biotite and light green actinolite. Biotite is replaced by chlorite and

epidote, this last mineral being present as small elongated crystals along the cleavage planes of the biotite. K-feldspar is absent or very scarce. Sphene, apatite, zircon, tourmaline and magnetite are accessories. Alteration of the tonalite is widespread and is indicated by the presence of epidote, chloritization of biotite, actinolitic hornblende and partial sericitization of plagioclase. Modal analyses of the tonalite are given in Table 1, N° 1 and GO-2 and in Figure 9.

The country rock adjacent to the orbicular body has been studied at contacts 1 and 2.

At Contact 1 the country rock is a light gray, medium to coarse-grained granodiorite with hypidiomorphic texture, consisting of plagioclase, quartz, chloritized biotite, K-feldspar and abundant epidote (modal analysis given in Table 1, N° 3 and Fig. 9). Plagioclase is strongly sericitized; where fresh areas are preserved a composition of An_{40} has been obtained but albitic zones have also been observed. Quartz is anhedral, transparent and has a marked wavy extinction. K-feldspar is relatively abundant and is not altered. Chlorite is present and mainly replaces biotite (and amphibole?). It is commonly associated with epidote. Epidote is abundant and is present as individual crystals, as an alteration product of plagioclase and ferromagnesians and also as veinlets.

The quartz diorite at Contact 2 is a medium to dark gray, medium-grained rock composed of plagioclase, amphibole, biotite, quartz, clinopyroxene and K-feldspar (modal analysis given in Table 1, N° 2 and Fig. 9). The rock has a hypidiomorphic to allotriomorphic granular texture with an average crystal size of 2–3 mm. Plagioclase is An_{42} and no zoning is observed although several crystals have an antiperthitic texture. The amphibole is a dark green hornblende with relic clinopyroxene cores commonly preserved. Biotite is generally fresh and is only partially altered to chlorite and rarely epidote. White mica flakes are rarely present as part of the biotite alteration. Smaller, rectangular biotite crystals, with their longest axis perpendicular to the cleavage traces of the major biotite grains are occasionally present probably representing a later generation. Quartz is anhedral and free from inclusions and it has a strong wavy extinction. The K-feldspar is present as large, irregular untwinned crystals poikilitically enclosing small plagioclase and amphibole crystals. Average modal analyses for the total country rock and for the country rock at the contacts with the orbicular body are given in Table 1 and Figure 9, N° 4 and N° 5 respectively.

The melanocratic dykes cutting across the orbicular body are fine-grained diabbases composed of plagioclase and clinopyroxene in ophitic intergrowth with abundant interstitial minute crystals of magnetite. Pale amphibole needles

are present in subordinate amount and accessory biotite is associated with lamellar ilmenite. In one specimen, clinopyroxene is uralitized in various degrees and crosscutting veinlets of plagioclase and amphibole are present. Some dykes are porphyritic with large (up to 1.5 cm) glomerophenocrysts of oscillatory zoned plagioclase in a groundmass of plagioclase and uralitized clinopyroxene; in this type of rock green biotite, tourmaline and iron ores are the main accessory minerals.

Petrography of the orbicular rock

The orbicules

Morphology — Orbicules are predominantly spheroidal and ellipsoidal. Observations on 100 individuals indicated that only 15 of them depart from the spheroidal-ellipsoidal morphology, and have kidney-like, heart-like or triangular forms with rounded corners when observed on the surface of the outcrop.

The average apparent size based on the same morphological set of orbicules gave values of 7–8 cm for the major axis (A_1) and 5–7 cm for the minor axis (A_2) (Fig. 4, a and b). The contact between the orbicules and the matrix is sharp.

Structure and petrography — Orbicules are composed of a core and a shell.

The Core.— The most frequent dimensions for the core correspond to a major axis (a_1) of 3–4 cm and a minor axis (a_2) of 2–3 cm (Fig. 4, c and d). Relationships between core size and total orbicule size give 0.524 and 0.500 as the commonest values for the ratios of a_1/A_1 and a_2/A_2 respectively (Fig. 5). The contact between core and shell is poorly defined and microscopically marked by a rather sinuous contour (Fig. 6 and Fig. 7).

The core is polycrystalline and corresponds to a medium gray, medium-grained (1.5 to 2.0 mm) quartz diorite composed of plagioclase, amphibole, quartz, biotite, small amounts of K-feldspar, clinopyroxene, and accessories, mainly magnetite (Table 1, N°9 and Fig. 9). The texture is hypidiomorphic granular. Plagioclase crystals are subhedral and generally normally zoned from An_{72} to An_{48} . In zoned plagioclases the cores have “patchy” appearance and are partly or completely enveloped by a clear, homogeneous sodic rim where polysynthetic twinning is well developed. The boundary between the homogeneous rim and the “patchy” core is sharp and both parts are optically discontinuous; nevertheless twinning has been observed crossing from one part to the other without optical change. In some of these zoned plagioclase crystals, a close spatial relationship exists between the outer clear rim and interstitial quartz and K-feldspar. This latter mineral extends as a narrow fringe

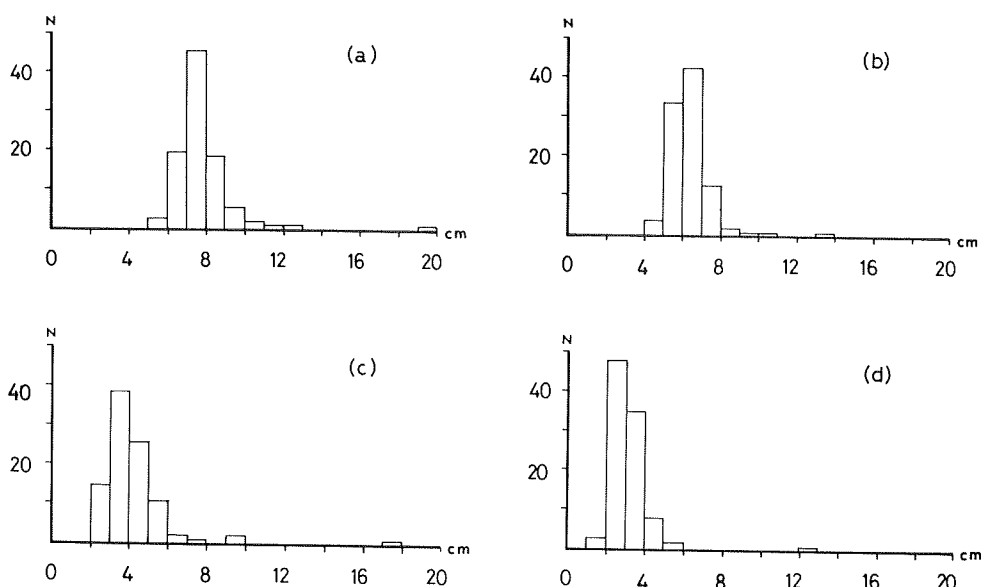


Fig. 4 Distribution of size, main axes of total orbicule and core. a) Total orbicule, major axis (A_1); b) Total orbicule, minor axis (A_2); c) Core, major axis (a_1); d) Core, minor axis (a_2).

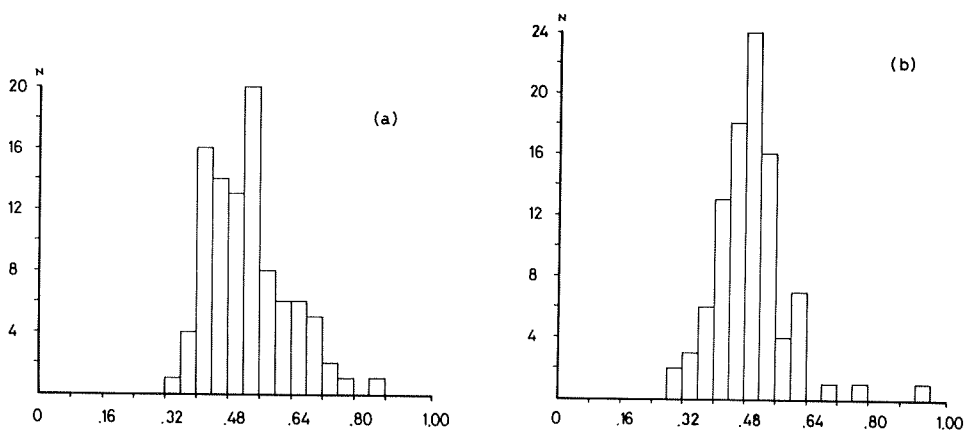


Fig. 5 Distribution of values for the ratio Core axis/Total orbicule axis. a) Ratio a_1/A_1 ; b) Ratio a_2/A_2 . Axes letters, same as in Figure 4.

following the outer boundary of the plagioclase rim and separates it from larger, anhedral, interstitial-type quartz grains. Quartz is also surrounded by a similar fringe of K-feldspar that separates the grains from other plagioclase crystals. Compositions ranging from An_{48} to An_{64} have been obtained for unzoned plagioclases. The 20(131) – 20(131) values (Smith and Yoder, 1956)

indicate a low structural state for the plagioclases in the orbicule core.

Two types of amphibole are present. One is a brownish-green, subhedral, homogeneous hornblende; relic clinopyroxene cores are preserved in some of these amphibole crystals. The other type is commonly zoned and irregular in shape with embayed and corroded boundaries. It is green to slightly bluish-green in colour with darker rims. Granular magnetite is typically associated with the latter amphibole and clinopyroxene is observed as cores in these amphiboles. Amphibole, especially those of the former type, tend to form an ophitic intergrowth with plagioclase or poikilitically enclose fragments of plagioclase.

Quartz is always interstitial and has a weak wavy extinction; in several cases it encloses fragments of plagioclase.

Biotite is rather scarce and in places it is closely related to amphibole although contacts between both minerals are generally well defined. Alteration to chlorite and epidote along the cleavages of the biotite is not common.

K-feldspar is locally concentrated as large anhedral, non-perthitic, slightly turbid crystals that have invaded plagioclase along fractures planes. Corroded and embayed fragments of plagioclase occur as numerous, optically continuous, "island" poikilitically enclosed by K-feldspar. Twin lamellae can be traced from one fragment of plagioclase to the other showing that no considerable movement or distortion took place during the growth of the K-feldspar.

The Shell.— The shell corresponds to the single shell type of Leveson (1966) although different zones can be microscopically defined based on mineralogical and/or textural changes. This zoning is sometimes megascopically observed in the orbicules, especially on polished slabs.

The contact between the shell and the matrix is sharp and is defined by a thin envelope of biotite. The contact between the shell and the core is ill-defined megascopically. Microscopically it is marked by the disappearance of quartz in the shell and the textural change from hypidiomorphic granular texture of the core to a radial intergrowth of plagioclase and amphibole that characterizes the inner part of the shell (Fig. 6 and Fig. 7).

The following description of the shell refers to the circular sectors of Figures 6 and 7 comprising the core and the whole shell up to its contact with the matrix.

Six zones have been distinguished in the shell. They are texturally characterized by a regular decrease in crystal size from the inner to the outer zones and by slight changes in the mineralogy. These zones, from the core boundary to the matrix, are: 1) Non-radial, Amphibole + Plagioclase Zone; 2) Radially intergrown, Amphibole + Plagioclase Zone; 3) Radial, Amphibole + Plagioclase + Clinopyroxene + Magnetite + (Biotite) Zone; 4) Non-radial,

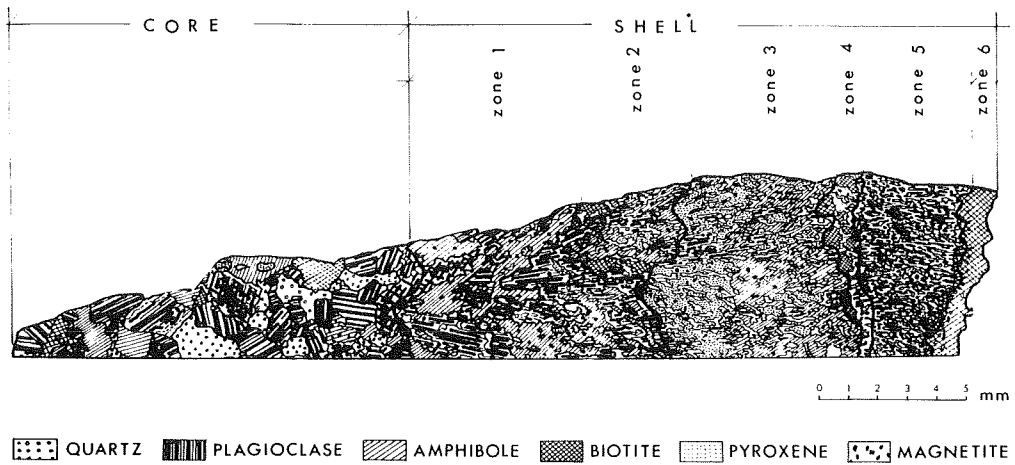


Fig. 6 Sector of an orbicule showing mineralogy, texture and division of the shell in six zones as follows: Zone 1) non-Radial, Amphibole + Plagioclase; Zone 2) Radially intergrown, Amphibole + Plagioclase; Zone 3) Radial, Amphibole + Clinopyroxene + Plagioclase + Magnetite + (Biotite); Zone 4) Non-Radial, Biotite + Amphibole + Plagioclase + Magnetite + (Clinopyroxene); Zone 5) Radial, Plagioclase + Amphibole + Magnetite and Zone 6) Non-Radial, Biotite envelope.

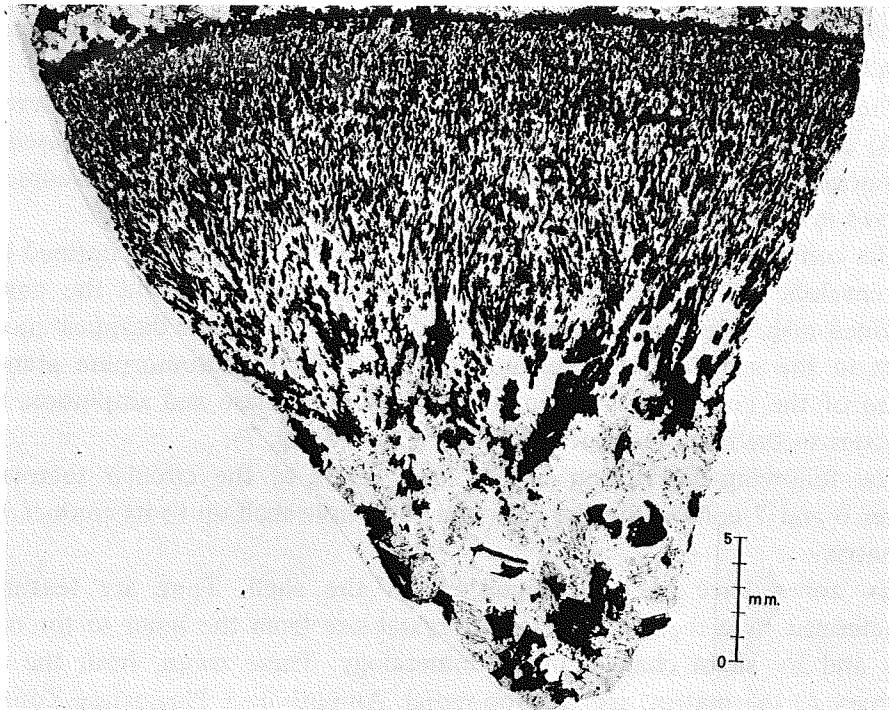


Fig. 7 Circular sector of an orbicule showing core and shell. Photograph taken by projection of a thin section. Plane polarized light.

Biotite + Amphibole + Plagioclase + Magnetite + (Clinopyroxene) Zone; 5) Radial, Plagioclase + Amphibole + Magnetite Zone and 6) Non-radial, Biotite envelope Zone.

The Non-Radial, Amphibole + Plagioclase Zone (Zone 1) is an average of 3.5 mm in thickness consisting of large hornblende crystals of the zoned type with lighter, greenish central parts. In some individuals clinopyroxene cores are present; magnetite grains are rather scarce. Plagioclase crystals are in places enclosed by hornblende and some of them are optically continuous with the radial plagioclase that characterizes Zone 2. A small amount of biotite is also present in Zone 1.

The Radially intergrown Amphibole + Plagioclase Zone (Zone 2) is made up of elongated crystals of both minerals with irregular and embayed margins arranged in a "feather-like" or "fan-like" fabric. Amphibole and plagioclase are present in equal amounts. The average size of the longest axis of the crystals is 2.5 mm. Hornblende contains more numerous pyroxene cores than the amphiboles of Zone 1. In several places, amphibole crystals poikilitically enclose "feather-like" plagioclase whose twinning follows the general radial pattern of the zone. Magnetite and biotite are rarely found.

The Radial Amphibole + Clinopyroxene + Plagioclase + Magnetite + (Biotite) Zone (Zone 3) has a transitional contact with Zone 2 marked by a progressive increase in clinopyroxene that becomes as abundant as the amphibole. Pyroxene is partially replaced by amphibole which occurs as rims in the pyroxene. Plagioclase is also a main constituent. Magnetite is more abundant than in Zones 1 and 2 and is generally associated with the ferromagnesian minerals. Biotite is very scarce. A reduction in crystal size is observed in the outer part of zone 3 accompanied by a slight decrease in clinopyroxene and a minor increase in biotite. Average crystal size in this outer part is of 1.0 to 1.5 mm.

The Non-Radial Biotite + Amphibole + Plagioclase + Magnetite + Clinopyroxene Zone (Zone 4) forms a narrow band approximately 1.0 mm thick, where biotite with an average size of 0.8 mm is clearly predominant. Biotite crystals are arranged perpendicular to the elongation of crystals in the other zones. The radial texture is thus partially interrupted here. Clinopyroxene is present mainly as remnant cores in amphibole.

The Radial Plagioclase + Amphibole + Magnetite Zone (Zone 5) is characterized by a high concentration of magnetite. Elongated grains of magnetite with an average size of 0.2 mm are arranged radially. Plagioclase largely predominates over amphibole and clinopyroxene and biotite is rarely present. Spinel is a common accessory mineral. In some orbicules, the outermost area of Zone 5 is characterized by a textural change of plagioclase

from radial bostonitic to granoblastic and by the disappearance of magnetite. This outermost area has a maximum width of 0.3 mm but is discontinuous. In some orbicules, Zone 6 is partially absent and the granoblastic area is in direct contact with the matrix.

The Biotite envelope Zone (Zone 6) consists of an outer rim, 0.5 to 1.0 mm thick where biotite crystals are oriented perpendicular to the axes of the radial arrangement of the inner zones. This biotite rim is very continuous in most of the orbicules and marks the boundary between orbicule and matrix. Two parts can be distinguished in this zone separated by a thin alteration fringe. The inner biotite has a highly poikilitic nature and encloses granoblastic plagioclase belonging to the outermost, magnetite-free part of Zone 5. This inner biotite is separated from an outer biotite band by an altered fringe, approximately 0.05 to 0.1 mm thick, mainly consisting of small grains of epidote. The outer biotite is non-poikilitic and is mantled by a thin dark border adjacent the alteration zone. Some small biotite flakes, optically discontinuous in relation to the outer biotite, have been observed as part of the alteration fringe. The outer biotite crystals have their cleavage directionally coincident with that of the inner poikilitic biotite. In some parts, the outer biotite occurs side by side with amphibole and both minerals transitionally pass to the hypidiomorphic fabric of the matrix. In some places the crystals of outer biotite are extensively altered to chlorite and the inner poikilitic biotite is absent so that the epidote-alteration fringe is in direct contact with Zone 5.

Thin fractures filled by a light green amphibole cut across the orbicules.

Modal analysis of the whole shell, comprising the six zones described, is presented in Table 1, N° 10 and in Fig. 9.

Based on this analysis and on the mode corresponding to the core, a modal composition was calculated for the total orbicule based on a volume ratio of 1 : 8 between core and shell. This ratio was obtained by assuming a spheric shape for the orbicule and the core and by taking a diameter ratio of core/total orbicule = 1/2 as indicated from the axes ratio of Fig. 5. Results obtained are shown in Table 1, N° 8, and Figure 9.

The matrix

The matrix is a light yellowish-gray, medium to coarse-grained porphyritic granodiorite. The most prominent feature in this rock is the presence of abundant phenocrysts of K-feldspar with an average size of 4 cm and a maximum of 9 cm. They are commonly located at the boundary with the orbicules or filling inter-orbicular spaces and amount to approximately 15 percent of the total rock. Concentration of K-feldspar crystals results in a

pegmatitic character for the matrix in many places. Crystals of randomly oriented prismatic hornblende, 0.2 cm are also present in this matrix.

The groundmass is a medium-grained tonalite of hypidiomorphic granular texture with an average crystal size of 3–5 mm consisting of quartz, plagioclase, biotite, K-feldspar and amphibole. Sphene, apatite and magnetite are accessories and sericite, epidote and chlorite are present as alteration minerals. Quartz is always anhedral and typically has strong wavy extinction; it generally poikilitically encloses other components, mainly plagioclase. Plagioclase commonly has normal zoning from An_{60} – An_{48} . In several unzoned crystals, compositions ranging from An_{48} to An_{52} were obtained. Plagioclase is commonly altered to sericite, particularly in the core or along zone boundaries. The $2\theta(131) - 2\theta(\bar{1}\bar{3}1)$ value indicates a low structural state for these plagioclases. Biotite is present as subhedral, short prismatic crystals, commonly fresh; some of them show alteration to chlorite, epidote and white mica. In several cases biotite poikilitically encloses plagioclase. Small amount of K-feldspar is present in the groundmass (approximately 2 percent) and occurs as anhedral, slightly perthitic, interstitial crystals, commonly enclosing corroded plagioclase. The amphibole is a greenish hornblende commonly homogeneous especially in the case where it occurs as twinned prisms. Some crystals are zoned with light green cores. Cores of clinopyroxene, although scarce, have been observed in some amphiboles. A modal analysis of the matrix groundmass is given in Table 1, N°6 and in Figure 9. A modal analysis of the whole matrix was calculated based on the mode of sample 6 and the known average percentage of K-feldspar phenocrysts (Table 1, N°12, Fig. 9).

The inclusions

Inclusions are rare in the orbicular rock; no more than 3 or 4 have been observed in the outcrop. The most typical correspond to a half-ellipsoid with rounded edges and 11 cm as a maximum size, and to a well rounded ellipsoidal body with axes of 35 and 28 cm. In this last inclusion a narrow and continuous outer rim of biotite is present.

The main inclusion (Table 1, N°7, Fig. 9) is a medium gray, medium-grained granodiorite composed of plagioclase, amphibole, quartz, biotite and K-feldspar. Crystals have an average size of 2–3 mm. Epidote and chlorite are abundant as alteration minerals. The texture is hypidiomorphic to allotriomorphic. Plagioclase (An_{54}) is generally unzoned and “patchy”; no clear rim is observed as in the plagioclase from the orbicule core and sericitization is widespread. The amphibole is a brownish-green hornblende; some crystals have been partly replaced by biotite and most of them enclose clinopyroxene cores.

Quartz is anhedral, interstitial, and has a strong wavy extinction. Biotite is largely altered to chlorite and epidote specially along cleavage planes. Tourmaline is present as an accessory mineral.

The contact with the country rock

The sinuous and regular comb layering band present at Contact 1 has been microscopically studied. The dark band adjacent to the orbicular body has been covered in a width of approximately 15 mm of thin section (Fig. 8). The layers are here mainly composed of plagioclase, amphibole, biotite and magnetite with a grain size of 2–3 mm and closely resemble those from the shell, both in texture and mineralogy. Clinopyroxene is present as cores in several amphibole crystals. Epidote is an alteration mineral.



Fig. 8 Part of the comb layering band at Contact 1. The photograph shows a section of the dark layer closest to the orbicular body and was taken by projection of a thin section. Plane polarized light.

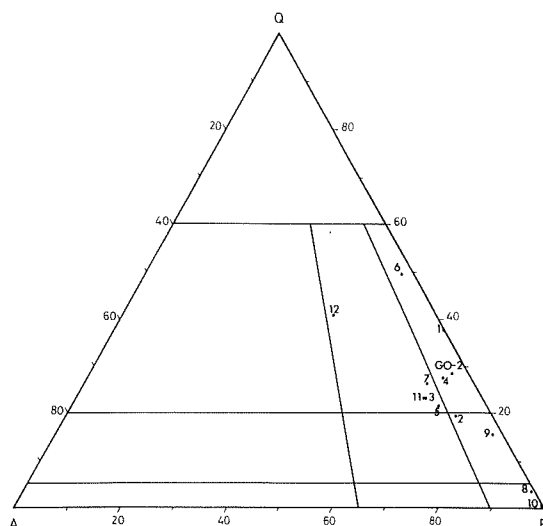


Fig. 9 Modal data for the orbicular and related rocks. Numbers are the same as in Table 1.

Plagioclase is finely twinned, irregularly shaped, “feather-like” type and is oriented with its longest dimension and twin lamellae perpendicular to the layering. Plagioclase is generally “patchy” and some individuals are zoned by a clear homogeneous sodic outer rim. The composition in several unzoned

crystals varies from An_{38} to An_{55} . Amphibole crystals have grown in a more disordered way, nevertheless many are arranged perpendicular to the layering. Crystals closest to the matrix of the orbicular body are particularly poikilitic and enclose equigranular, mosaic-like plagioclase. The amphibole is a green hornblende, partly colour zoned, especially around clinopyroxene cores. Biotite is largely parallel to the strike of the layering. Magnetite is abundant in the layers but nearly absent in the area of matrix covered by the thin section.

Taken as a whole rock, this part of the banded contact would correspond to a diorite.

	1	2	3	4	5	6	7	8	9	10	11	12	GO-2
Quartz	26.2	10.6	18.0	17.7	14.3	40.8	13.5	1.7	12.0	0.2	13.3	34.7	15.8
Plagioclase	43.7	40.4	51.1	43.2	45.7	39.8	33.4	42.8	62.6	39.9	37.5	33.8	37.6
Amphibole	10.7	21.1	-	12.7	10.6	1.5	17.3	37.0	18.2	39.6	25.1	1.3	19.0
Biotite	14.0	19.0	11.6	12.7	15.3	11.0	13.3	4.3	4.3	4.7	6.5	9.4	6.4
K-feldspar	-	3.8	8.3	3.5	6.1	1.7	4.7	0.2	1.5	-	6.2	16.4	1.7
Pyroxene+Accessories+Alteration Minerals	5.4	5.1	11.0 <i>E only</i>	10.2	8.0	5.2	17.8	7.6P 2.3E+S 4.1M	1.2P 0.2M	8.4P 2.6E+S 4.6M	11.4	4.4	19.5
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Q	37.7	19.3	23.3	27.5	21.6	49.6	26.2	3.8	15.8	0.6	23.3	40.8	28.7
A	-	7.0	10.7	5.4	9.3	2.1	9.1	0.5	2.0	-	10.9	19.4	3.2
P	62.3	73.7	66.0	67.1	69.1	48.3	64.7	95.7	82.2	99.4	65.8	39.8	68.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Plagioclase composition	An_{48-52}	An_{42}	$An_{40\&An_{40}}$	-	-	$An_{48-60}^{z,u}$ $An_{48-52}^{z,u}$	An_{54}	-	$An_{48-72}^{z,u}$ $An_{48-64}^{z,u}$	An_{50}	-	-	An_{48-52}
Total Ferro-magnesian	30.1	45.2	22.6	35.6	33.9	17.7	48.4	55.3	23.9	59.8	43.0	15.1	44.9
Amphibole/Biotite	0.8	1.1	-	1.0	0.7	0.1	1.3	8.6	4.2	8.4	3.9	0.1	3.0

P: pyroxene, E: epidote, S: sphene, M: magnetite, z: zoned, and u: unzoned.

- Country rock, 0.5 km to the north of the orbicular body.
- Country rock, Contact 2.
- Country rock, Contact 1.
- Average country rock. Includes samples 1, 2, 3 and GO-2.
- Average country rock, contacts 1 and 2. Includes samples 2 and 3.
- Matrix of the orbicular rock, excluding K-feldspar phenocrysts.
- Largest non-orbicular inclusion.
- Total orbicule. Calculated from analyses 9 and 10.
- Core of orbicule (average of 4 samples, one of them No.9 Table 2).
- Shell of orbicule.
- Rock 1. Calculated from analyses 10 and 12.
- Matrix plus K-feldspar phenocrysts. Calculated by addition of phenocrysts to analysis 6.
- GO-2. Country rock, 0.5 km to the south of the orbicular body.

Table 1. Modal Analyses in volume percent of the orbicular and related rocks.

Comparative petrographic features of matrix, orbicule, inclusions and country rock

The predominant texture for the majority of rock types is hypidiomorphic to allotriomorphic granular with an average crystal size of 2–3 mm. Exceptions are the porphyritic texture of the matrix, the only rock type where large phenocrysts of K-feldspar up to 9 cm have been observed, and the shell and comb layering contact where the crystals have a radial or comb-like arrangement.

The mineralogical assemblages are combinations, in different proportions, of plagioclase, amphibole, quartz, biotite, K-feldspar and clinopyroxene. Most of the rocks plot in the tonalite, quartz diorite and diorite fields of Figure 9. The presence of relic pyroxene in all the rocks described and as single grains and/or as relictic cores in the shell of the orbicules, is a particular feature. Magnetite is peculiarly concentrated in the orbicules and in the comb layering contact. The highest concentration of magnetite is found in the shell (4.6 percent) where it is a main constituent in the outermost zones.

Plagioclase has a relatively constant composition averaging An_{50} and having a higher An content in the core of the orbicules. Plagioclase is commonly zoned, "feather-like" and radially arranged in the orbicules and comb layering contact and has a "patchy" texture with a homogeneous overgrown rim in some individuals of the core and comb layering contact. Plagioclases from the core and the matrix have a low structural state.

The ferromagnesian content is high in the shell (59.8 percent) of the orbicules and in the non-orbicular inclusion (48.4 percent) and reaches the lowest value in the matrix (15.1 percent). The amphibole/biotite ratio has a maximum value of 8.4 in the shell of orbicules and a minimum value of 0.1 in the matrix. For the average country rock this ratio is 1.0.

Alteration mainly affects the country rock and the matrix and is strongest in the country rock around Contact 1 where it appears to be related to the fracture system. The main alteration minerals are epidote, chlorite and sericite; minor amounts of white mica partially replace biotite. Actinolitic amphibole and a younger generation of biotite also belong to the alteration mineral assemblage. The orbicules (core and shell) are almost completely free of alteration except for the epidote fringe at the outer biotite envelope of the shell and the presence of minor epidote and chlorite inside biotite in the core.

Compositional differences are observed when comparing the different samples of country rock, country rocks versus orbicules (core and shell), core versus shell of orbicules and all of these different types with the matrix. These variations are shown in Figure 9 and Table 1.

Country rocks located far from the orbicular body (Table 1, N°1 and GO-2) are richer in quartz and poorer in K-feldspar in comparison with the average composition of the country rock at Contacts 1 and 2 (Table 1, N°5). Nearer the orbicular body, there is slight increase in the ferromagnesian content in the country rock with the exception of the highly altered country rock at Contact 1 (Table 1, N°3).

When comparing the core of the orbicules and the average country rock there is a decrease in the amount of quartz, K-feldspar and total ferromagnesians in the core together with a strong increase in plagioclase and in the

amphibole/biotite ratio. When the shell of the orbicule is compared to the average country rock the absence of quartz and K-feldspar in the shell is the most striking feature. The total amount of ferromagnesian strongly increases in the shell and the ratio of amphibole/biotite is enlarged 8.5 times. The plagioclase content is almost constant, slightly lower in the shell, 39.9 percent, compared to 43.2 percent in the average country rock. Similar comparative features exist between the core and the comb layering portion at Contact 1.

If the core is compared to the shell an increase in the ferromagnesian content of 2.5 times is observed in the shell; a significant aspect of this increase being the unusually abundant amount of pyroxene and magnetite (13 percent together) in some zones of the shell. The ratio of amphibole/biotite is doubled in the shell. The plagioclase percentage strongly decreases in the shell by an approximated factor of 1.5. A comparison of the largest non-orbicular inclusion and the average country rock shows a remarkable petrographic similarity. Slight increases in the percentage of ferromagnesian minerals, plagioclase, K-feldspar and in the ratio amphibole/biotite by factors varying between 1.2 and 1.4 occur in the inclusion. Quartz decreases in the inclusion by a factor of 1.3.

When the mineralogical composition of the non-orbicular inclusion is compared to that of the core, plagioclase increases by a factor of 1.9 and the ratio amphibole/biotite increases by a factor of 3.3 in the core. There is a decrease in the amount of ferromagnesian minerals by a factor of 2.0 and of K-feldspar by a factor of 3.2 in the core. The amount of quartz remains almost constant and decreases slightly in the core.

The total matrix (Table 1, N°12) has very different mineralogical and textural features in comparison with the other rock types. It has the highest percentage of quartz and K-feldspar and the smallest amphibole/biotite ratio. The presence of large phenocrysts of K-feldspar also characterizes this rock. All these features would indicate that this is the most differentiated unit among the rocks studied.

A descriptive classification of the orbicules following Leveson (1966, p. 421) would be as follows: Rock type, Tonalite; Structure, Single-Shell; Texture, R (radial)-pl. hb, px, mag; T (tangential)-bi, Core Type, UM (Dissimilar to matrix).

Chemistry of the country and orbicular rocks

Chemical analyses of country rock, matrix of the orbicular body, whole orbicule, orbicule core, non-orbicular inclusion and mafic dykes cutting across the orbicular body, CIPW norms, D. I. (Differentiation Index, Thornton and

Tuttle, 1960), oxidation ratio $\text{Fe}_2\text{O}_3/\text{FeO}$, and normative parameters An, Ab, Or and Ab, Or, Q are given in Table 2.

A chemical analysis was calculated for the shell of the orbicule (Table 2, N°10) based on the analyses of the total orbicule and the core (Table 2, N°8, and N°9). Calculation was done assuming the same relationships as for the modal analysis N°8 of Table 1 already explained.

The composition of the whole matrix (Table 2, N°12) was calculated from the chemical analysis of the matrix groundmass (Table 2, N°6) adding to it a 15 percent of K-feldspar phenocrysts. The composition of the K-feldspar was taken after Leveson (1963, Table 3, N°4, p.1034) as: SiO_2 : 64.7 percent, Al_2O_3 = 18.4 percent and K_2O = 16.9 percent.

The composition of a "rock" Σ (Table 2, N°11) formed by the addition of the whole matrix and the shell was obtained based on the calculated analysis of the whole matrix, the calculated analysis of the shell, the ratio 35/65 between matrix and orbicules at the outcrop and the diameter ratio 2 : 1 between total orbicule and core assuming them to be spherical.

A rock sequence is arranged in order to show the oxide variation. This sequence is arranged from the outer country rock (average value) to the core of the orbicules as follows:

1) Average country rock, 2) Non-orbicular largest inclusion, 3) Whole matrix, 4) Shell of the orbicules, 5) Total orbicule and 6) Core. In order to emphasize the variations present the diagram has been constructed symmetrically except for the non-orbicular inclusion (Fig. 10).

The variation in the normative amounts of Ab, Or, Q and An, Ab, Or are presented in Figure 11 together with the data of Kobayashi (1972).

Trace element abundances and some selected ratios determined for the same set of rocks are given in Table 3 and plotted in Figures 12 and 13. Trace element composition of the K-feldspar phenocrysts was not available, so, the trace element content for the whole matrix could not be calculated and the matrix groundmass (Tables 1, 2 and 3, N°6) values were used for comparative diagrams. D. I. variation is represented in Figure 10 and values of D. I. plotted against major oxides in Figure 14.

The main features obtained from these diagrams and tables are summarized as follows:

(1) All the rocks are oversaturated with the exception of the total orbicule and the shell that are saturated and have normative olivine.

(2) D.I. values vary from 28.67 for the shell to a maximum of 60.46 for the matrix. The linear arrangement of points in the D. I. versus oxides diagrams (Fig. 14) indicate a cogenetic relationship between the orbicular body and the country rock. A simple variation diagram SiO_2 vs. oxides (not included here)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO ₂	61.22	55.42	58.03	58.22	56.73	61.71	56.25	49.24	54.10	48.55	53.72	62.15	53.16	54.71
TiO ₂	0.92	0.73	0.34	0.66	0.54	0.95	0.85	0.54	0.37	0.56	0.66	0.81	2.90	2.46
Al ₂ O ₃	16.10	17.05	17.19	16.78	17.12	14.99	16.41	18.55	16.69	18.81	17.55	15.50	13.94	14.26
Fe ₂ O ₃	1.58	1.80	1.88	1.75	1.84	2.28	1.63	2.35	1.90	2.41	2.23	1.94	2.44	2.39
FeO	5.38	6.07	4.02	5.16	5.05	4.56	5.72	7.74	4.86	8.15	6.52	3.88	10.68	9.54
MnO	0.13	0.13	0.05	0.10	0.09	0.11	0.13	0.17	0.09	0.18	0.15	0.09	0.20	0.20
MgO	2.56	5.10	2.70	3.45	3.90	2.28	4.80	4.27	3.66	4.35	3.44	1.94	3.02	4.11
CaO	6.02	8.21	6.20	6.81	7.21	6.42	7.86	12.05	12.14	12.03	9.54	5.48	6.52	5.79
Na ₂ O	2.81	2.48	2.98	2.76	2.73	2.22	2.27	2.58	2.67	2.57	2.31	1.89	4.61	4.32
K ₂ O	1.59	2.64	2.54	2.26	2.59	1.78	1.78	1.22	1.54	1.18	2.27	4.05	0.96	0.94
P ₂ O ₅	0.21	0.16	0.38	0.25	0.27	0.35	0.28	0.35	0.36	0.35	0.33	0.30	0.70	0.49
Ig. loss	1.22	0.58	3.35	1.72	1.97	2.57	1.90	1.01	1.24	0.98	1.44	2.18	0.65	0.60
Total	99.74	100.37	99.66	99.92	100.04	100.22	99.88	100.07	99.62	100.12	100.16	100.21	99.78	99.81
Fe ₂ O ₃ /FeO	0.29	0.30	0.47	0.34	0.36	0.50	0.28	0.30	0.39	0.30	0.34	0.50	0.23	0.25
C. I. P. W. NORMS (calculated on water free basis)														
Q	19.76	4.81	12.79	12.43	8.82	24.31	11.09	-	5.32	-	5.83	20.64	3.00	5.33
Or	9.35	15.58	14.97	13.30	15.25	10.46	10.46	7.18	9.07	6.96	13.36	23.88	5.62	5.51
Ab	23.75	20.97	25.17	23.33	23.07	18.77	19.19	21.81	22.55	21.71	19.50	15.94	38.96	36.49
An	26.65	27.59	26.04	26.73	26.84	25.70	29.35	35.44	29.01	36.30	30.85	21.89	14.55	16.77
Wo	0.85	5.09	1.06	2.35	3.05	1.72	3.36	9.31	12.15	8.92	6.07	1.47	5.71	3.80
En	6.37	12.70	6.71	8.58	9.71	5.67	11.94	6.61	9.10	4.95	8.56	4.83	7.52	10.23
Fs	7.29	8.69	5.37	7.14	7.02	5.13	7.99	7.27	6.91	5.66	9.33	4.35	13.19	11.86
Fo	-	-	-	-	-	-	-	2.81	-	4.11	-	-	-	-
Fa	-	-	-	-	-	-	-	3.40	-	5.18	-	-	-	-
Mt	2.27	2.59	2.71	2.52	2.66	3.29	2.36	3.40	2.73	3.47	3.22	2.80	3.52	3.45
Il	1.75	1.38	0.64	1.24	1.02	1.79	1.61	1.02	0.70	1.06	1.24	1.53	5.49	4.66
Ap	0.47	0.37	0.87	0.57	0.64	0.81	0.64	0.81	0.84	0.81	0.77	0.71	1.65	1.14
D. I.	52.86	41.36	52.93	49.06	47.14	53.54	40.74	28.99	36.94	28.67	38.69	60.46	47.58	47.33
An	44.23	43.02	39.35	42.19	41.19	46.79	49.75	55.00	47.85	55.87	48.42	35.47	24.61	28.53
Ab	40.02	32.69	38.03	36.82	35.41	34.17	32.53	33.85	37.19	33.42	30.61	25.83	65.89	62.09
Or	15.75	24.29	22.62	20.99	23.40	19.04	17.72	11.15	14.96	10.71	20.97	38.70	9.50	9.38
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Ab	44.93	50.70	47.55	47.55	48.94	35.06	47.10	75.23	61.04	75.72	50.40	26.36	81.88	77.10
Or	17.69	37.67	28.28	27.11	32.35	19.54	25.68	24.77	24.55	24.28	34.53	39.50	11.81	11.64
Q	37.38	11.63	24.17	25.34	18.71	45.40	27.22	-	14.41	-	15.07	34.14	6.31	11.26
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Analyst : M.Aguilar, Dept. of Geology, Univ. of Chile.

- Country rock, 0.5 km to the north of the orbicular body.
- Country rock, Contact 2.
- Country rock, Contact 1.
- Average Country rock, Includes samples 1, 2 and 3.
- Average country rock contacts. Includes samples 3 and 2 from contact 1 and 2 respectively.
- Matrix of the orbicular rock, excluding K-feldspar phenocrysts.
- Largest non-orbicular inclusion.
- Total orbicule.
- Core of orbicule.
- Shell of orbicule. Calculated analysis.
- Rock Σ . Calculated analysis.
- Matrix plus K-feldspar phenocrysts. Calculated analysis.
- Diabasic dyke crosscutting the orbicular body.
- Id.

Table 2. Chemical analyses and norms of the orbicular and related rocks.

shows the same linear trends for the rocks involved. Diabasic dykes cutting the orbicular body, represented in Figure 14, generally plot apart from the linear trends, a fact that would indicate different magmatic origin.

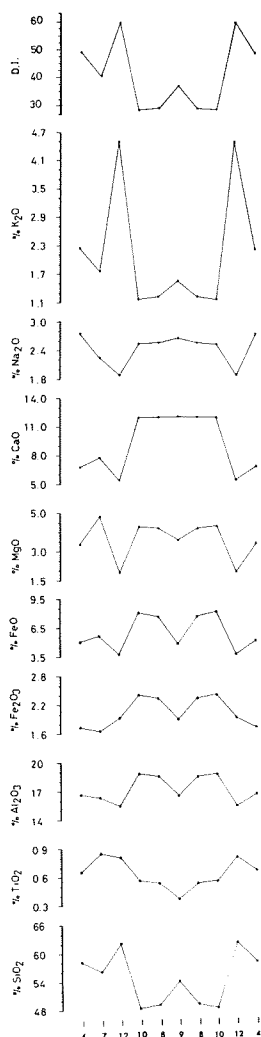


Fig. 10 Oxide content and D.I. variation in a sequence arranged from country rock (average composition) up to the core of the orbicules. The diagram has been constructed symmetric except for the non-orbicular inclusion. Numbers in abscissa correspond (as in Table 2) to: 4, Country rock average; 7, Largest non-orbicular inclusion; 12, Matrix plus K-feldspar phenocrysts; 10, Shell of orbicule; 8, Total orbicule; 9, Core of orbicule.

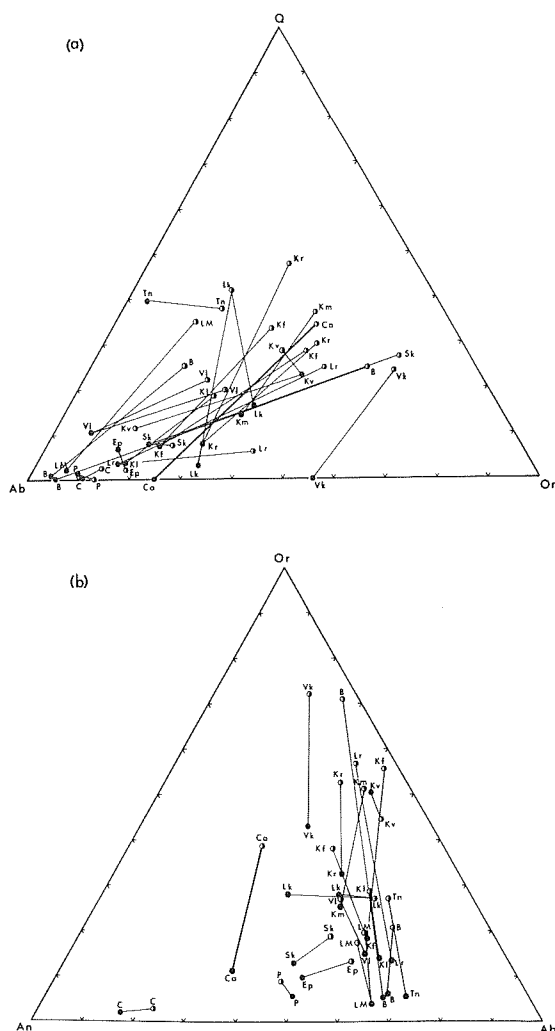


Fig. 11 a) Normative Ab-Or-Q diagram showing the relation between the matrix and the total orbicule. b) Same relation for the normative parameters An-Ab-Or. Data for the Caldera orbicular rock has been plotted for comparison on Kobayashi's Figs. 3 and 4 (1972, p. 106). B: Burein Mountain; C: Corsica; Ep: Espoo; Kf: Kortfors; Kl: Kangasala; Km: Kangasniemi; Kr: Kuru; Ku: Kemijarvi; LK: Laukaa; LM: Lonesome Mountain; Lr: Lintusaari; P: Pöytyä; Sk: Skällefte; Tn: Tissellilene; Vk: Virviik; Vl: Villpula; Ca: Caldera. Half black circle = matrix; dot = total orbicule.

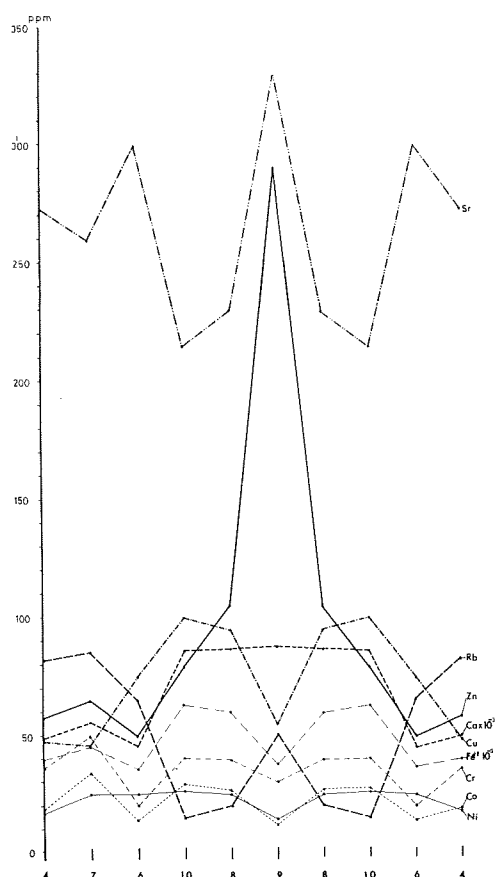


Fig. 12 Trace element content variations arranged in the same sequence as in Figure 10. Numbers in abscissa as in Figure 10 except that 12 is replaced by 6, matrix excluding K-feldspar phenocrysts (matrix groundmass).

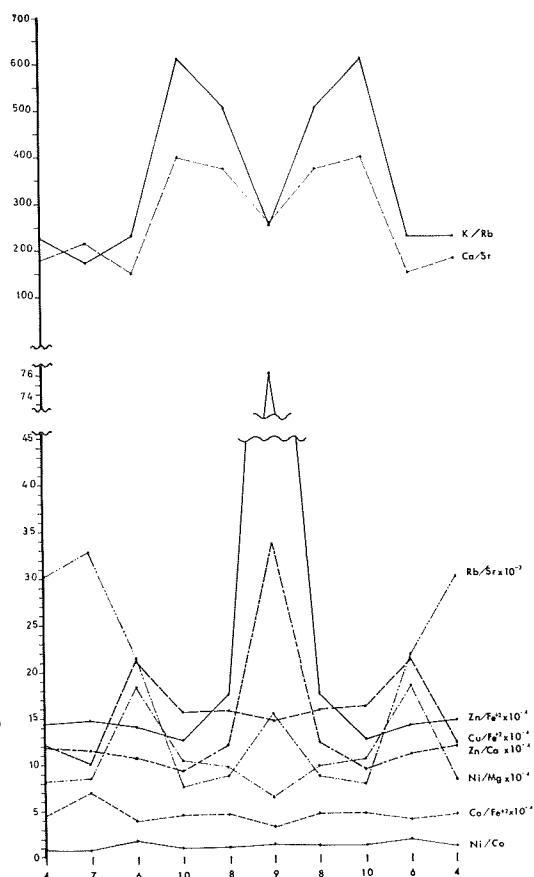


Fig. 13 Selected trace element ratios. Variations are presented as in Figures 10 and 12. Numbers in abscissa same as in Figure 12.

(3) The alkali-lime index for the series is between 61.5 and 64, corresponding to a calcic suite.

(4) Variation of major oxides in the different units of the orbicular body and the country rock (Fig. 10) shows that the matrix has the highest content in SiO_2 and K_2O and is lowest in Na_2O , CaO , MgO , FeO and Al_2O_3 . The average country rock has the maximum content of Na_2O , while the non-orbicular inclusion is the highest in MgO and TiO_2 and the lowest in Fe_2O_3 . The shell of the orbicules has the maximum amount of FeO , Fe_2O_3 and Al_2O_3 and the

	1	2	3	4	5	6	7	8	9	10	11	13	14
Cr	32	50	25	36	38	20	50	40	30	41	34	28	37
Ni	10	20	20	17	20	25	25	25	14	27	26	32	32
Co	18	22	14	18	23	14	32	27	12	29	24	70	32
Cu	55	55	35	48	40	75	45	95	55	101	92	135	95
Zn	70	70	35	58	53	50	65	105	290	79	69	100	110
Sr	250	250	320	273	285	300	260	230	330	216	244	220	240
Rb	55	80	110	82	98	65	85	20	50	16	33	25	7
Ca*	43043	58702	44330	48692	51516	45903	56199	86158	86801	86066	72411	46553	41341
Fe ^{+2*}	41964	47346	31356	40222	39351	35568	44616	60372	37908	63581	54056	83090	74221
Rb/Srx10 ⁻²	22.0	32.0	34.4	30.0	34.4	21.7	32.7	8.7	15.2	7.4	13.5	11.4	2.9
K/Rb*	240.0	274.0	191.7	228.8	219.4	227.4	173.9	506.4	255.7	612.3	571.1	318.8	1114.9
Ca/Sr	172.2	234.8	138.5	181.8	180.8	153.0	216.2	374.6	263.0	399.0	296.8	211.6	172.3
Zn/Fe ⁺² x10 ⁻⁴	16.7	14.8	11.2	14.4	13.5	14.1	14.6	17.4	76.5	12.4	12.8	12.0	14.8
Zn/Cax10 ⁻⁴	16.3	11.9	7.9	11.9	10.3	10.9	11.6	12.2	33.4	9.2	9.5	21.5	26.6
Ni/Co	0.6	0.9	1.4	0.9	0.9	1.8	0.8	0.9	1.2	0.9	1.1	0.5	1.0
Ni/Mgx10 ^{-4*}	6.5	6.5	12.3	8.2	8.5	18.2	8.6	9.7	6.3	10.3	12.5	17.6	12.9
Co/Fe ⁺² x10 ⁻⁴	4.3	4.6	4.5	4.5	5.8	3.9	7.2	4.5	3.2	4.6	4.4	8.4	4.3
Cu/Fe ⁺² x10 ⁻⁴	13.1	11.6	11.2	12.0	10.2	21.1	10.1	15.7	14.5	15.9	17.0	16.2	12.8

* Ca, Fe⁺², K and Mg calculated from the oxides.

Sample numbers as in Tables 1 and 2.

Table 3. Trace element analyses (ppm) and selected trace element ratios of the orbicular and related rocks.

minimum amount of K₂O and SiO₂. The core has the maximum content of CaO and a minimum of TiO₂.

(5) The highest Fe₂O₃/FeO ratio (0.50) corresponds to the matrix and the lowest (0.28) to the non-orbicular inclusion.

(6) A high concentration of CaO is present in the orbicules, shell and core all of them having similar values.

(7) Na₂O, MgO, FeO, Fe₂O₃ and Al₂O₃ values are similar for the average country rock and core. Differences between these two rocks are in their respective K₂O, SiO₂ and TiO₂ contents which are lower in the core and in the amount of CaO value which is higher in the core than in the average country rock.

(8) A comparison of the major oxides between core and shell of the orbicules shows that SiO₂, CaO, Na₂O, K₂O and P₂O₅ are more abundant in the core while Al₂O₃, Fe₂O₃, FeO, MgO, MnO and TiO₂ predominate in the shell.

(9) The comparative content of the trace elements among the different rock types is given in Figure 12. A notable feature is the high concentration of Zn and Sr in the core of the orbicules. Cu, Cr, Co and Ni are similar in core and average country rock; the core is higher in Sr and Zn and lower in Rb. Zn, Sr and Rb are more abundant in the core while Cr, Ni, Co and Cu are more concentrated in the shell.

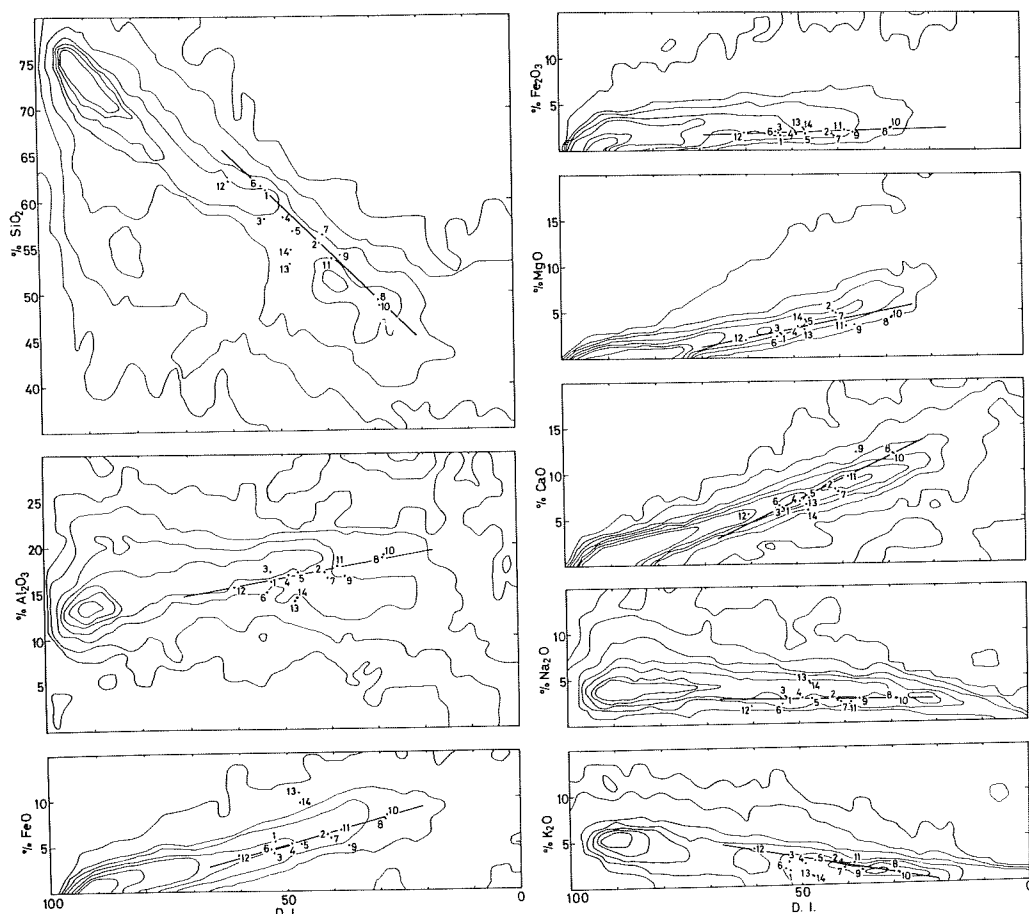


Fig. 14 Differentiation Index (D. I.) plotted against oxides. Numbers are the same as in Table 2.

(10) $\text{Zn}/\text{Fe}^{+2} \times 10^{-4}$ ratio is remarkably high in the core and reaches a minimum value in the shell; the same relationship is observed for the $\text{Zn}/\text{Ca} \times 10^{-4}$ ratio. The $\text{Rb}/\text{Sr} \times 10^{+2}$ ratio has maximum values in the country rock and the non-orbicular inclusion and its minimum value in the shell. The $\text{Ni}/\text{Mg} \times 10^{-4}$ ratio is highest in the matrix groundmass and minimum in the core. The K/Rb ratio is highest in the shell and lowest in the matrix groundmass and the non-orbicular inclusion. The Ni/Co ratio is very constant with a light increase in the matrix groundmass. The core and country rock show close similarities in the $\text{Ni}/\text{Mg} \times 10^{-4}$, K/Rb and Ni/Co ratios.

(11) The alteration observed at Contact 1 is indicated by an increase in K_2O , Al_2O_3 and Na_2O and a decrease in CaO , FeO and MgO in the country rock (Table 2, N°3).

Petrogenesis

Petrogenesis of the orbicular body is outlined on the basis of two main assumptions: 1) Non-orbicular inclusions in the orbicular body and the core of the orbicules correspond to country rock xenoliths; b) The shell of the orbicules and the matrix were generated from the same magma during differentiation.

a) The non-orbicular inclusions closely resemble the country rock from a megascopic point of view. In Figure 9, the largest non-orbicular inclusion (N°7) plots close to the total average country rock (N°4). When mineralogically compared to the nearest country rock at Contact 2 (Table 1, N°2), the inclusion shows a remarkable similarity in ferromagnesian mineral content (45.2 percent for the country rock and 48.4 percent for the inclusion) with amphibole \geq biotite. The chemical composition (Table 2) also indicates a close similarity for these two rocks with the only exception of K_2O that is higher in the country rock. These features indicate that the non-orbicular inclusion corresponds to a slightly transformed country rock. The alteration involved could be considered as the first stage of a progressive transformation from xenolithic country rock to the core of the orbicules. Such a tendency is illustrated in Figure 10.

When the core of the orbicules is chemically compared to the average country rock (Table 2) there is a close similarity with the exception of a notable enrichment in CaO and depletion in K_2O and SiO_2 in the core. Several common features between core and country rock have already been pointed out when comparing oxide content, trace element content and element ratios (Na_2O , MgO , FeO , Fe_2O_3 , Al_2O_3 , Cu , Cr , Co , Ni , $Ni/Mg \times 10^{-4}$, K/Rb and Ni/Co). The core of the orbicules has a lower ferromagnesian content (23.9 percent) and an amphibole/biotite ratio of 4.2 while the average country rock has 35.6 percent total ferromagnesian with amphibole equal to biotite. The modal amount of plagioclase in the core is 62.6 percent as against 43.2 percent for the country rock. The core has also less amounts of quartz and K-feldspar; all these features reflecting the main chemical differences already stated. It is also noteworthy that the closest country rock (N°2, Contact 2), taken separately from the average, plots nearest to the core (N°9) in Figure 9.

If several features show a similarity between core and country rock, differences in both chemistry and mineralogy would indicate that the xenoliths have not taken a passive role in the process. Petrographic observations of core samples would support this view. Among them, the presence of a clear, homogeneous and more sodic mantle enclosing most of the zoned plagioclase crystals, the "patchy" character of most of these plagioclases, the generation of

narrow K-feldspar bands closely following the outer border of the sodic plagioclase mantles and adjacent interstitial quartz; the generation of tiny patches of K-feldspar at the intersection of cleavages at the interior of "patchy" plagioclase individuals, the large anhedral and scattered K-feldspar crystals enclosing numerous islands of optically and morphologically continuous plagioclase; interstitial quartz poikilitically including plagioclase crystals; presence of at least two types of amphibole—one of them similar to the light green, zoned and magnetite-rich amphibole type of the shell, would account for the interaction of the xenoliths with a melt. Partial fusion corresponding to a lower melting point of the xenoliths would explain some of the described features. A large fraction of the primary SiO_2 and K_2O would have been expelled in this process and only a minor, interstitial fraction, would have remained in the xenoliths. Enrichment in CaO , the most particular characteristic of the core, could be explained relatively by the depletion in SiO_2 and K_2O and also by the interaction with the invading melt whose possible chemical nature will be described below. The same mechanism could explain the enrichment of the core in Zn and Sr.

The rather constant size of the xenolithic cores should be explained, as it is not statistically expected that fragmentation of the adjacent country rock would be size-selective. A mechanism of magmatic or fluid turbulence in the first stage of magma intrusion might explain this feature. The core shape, ellipsoidal or roughly spherical in a first approximation, is rather irregular under the microscope as the boundary between core and shell is not a sharp, geometrically well defined surface.

b) The shell of the orbicules and the matrix of the orbicular body are supposed to have been derived from a common magmatic source. An approximated composition for that magma can be obtained by combining the analyses of the shell and matrix considering their relative proportions in the orbicular body. The composition obtained has been termed rock Σ (Tables 1, 2 and 3, N° 11).

Rock Σ , as compared with the composition of the average country rock (Table 2, N° 5) has lower SiO_2 and Na_2O ; the remaining oxides are higher for rock Σ except for very similar values of TiO_2 and MgO . If compared to the average composition of the closest country rock at contacts 1 and 2 (Table 2, N° 5) rock Σ is lower in SiO_2 , Mg_2O , K_2O and MgO . The $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio is the same (0.34) for the rock Σ and the total average country rock.

Rock Σ would thus appear to be less differentiated than the average country rock supposed to have consolidated earlier, although as part of a cogenetic and broadly synchronous event (Farrar and others, 1970). This fact is not considered unusual as far as the trapping of fractionated volumes of magma

in "chambers" is a well known mechanism.

Whether the melt corresponding to rock Σ was present as a single magma or whether in fact it penetrated as an aqueous fluid phase plus magma, is difficult to infer. The existence of comb layering at Contact 1 would rather indicate the presence of a fluid phase such as in the mechanism postulated by Moore and Lockwood (1973).

Mutanen (1974, p. 64) has explained the formation of shells in orbiculite boulders from Sääkslahti, Toivakka, Finland, as the result of alternating local supersaturation and crystallization ahead of crystallization fronts. According to this mechanism "the monomineralic shells represent the crystallization of the excess phase, or when the magma is oversaturated in a few phases, the phase with the greatest nucleation power and the two phase layers resulted from eutectic or cotectic crystallization . . ." This is a well known hypothesis for the magmatic generation of orbicule shells (Leveson, 1966, p. 415) and recent support for it has come from different authors (see Mutanen, 1974, p. 63).

The interpretation of the results obtained for the orbicular body from Caldera agrees in many respects with the above mechanism. The mineralogical assemblages recognized in the shell include plagioclase, amphibole, clinopyroxene and some magnetite for the innermost (1–3) zones with an increasing amount of biotite and enrichment in magnetite at the outermost zones (4 to 6). This mineralogy is well explained by the chemical composition obtained for the presumed melt Σ , a magma rich in CaO, (FeO + Fe₂O₃), MgO and Al₂O₃. Minor amounts of Na₂O would be necessary to form the plagioclase (average An₅₀) and still minor for the amphibole. K₂O would exclusively go to form biotite, a very subordinated mineral phase in the innermost zones of the shell. According to this view, zones 1 to 3 would indicate supersaturation of the melt in amphibole followed by a cotectic crystallization (predominance of intergrown radial texture) of plagioclase and amphibole. Nevertheless, the ubiquitous presence of relic cores of clinopyroxene in amphiboles and the zoned character of most of these amphiboles would rather indicate that the pyroxene indeed was the primary mineral and that amphiboles are a product of widespread uraltization, a phenomenon also clearly observed in all the country rock specimens. This uraltization is here considered as the first stage of an autometamorphism-alteration process that culminated with the generation of the matrix and its residual fluid phases. Some of the magnetite, generally observed in close association with zoned amphiboles and uraltized pyroxenes could be interpreted as a product of this transformation.

The radial growth of the mafic minerals of the innermost zones would need a non-turbulent, low viscosity and hot melt A rather low Po₂, approximately represented by the ratio Fe₂O₃/FeO, would be also necessary in

the stage of shell formation. These conditions seem to be fulfilled by the melt Σ , close to an andesitic composition and with an oxidation ratio of 0.34. Undisturbed growth of the shell is reflected in the continuous and uniform bands of the plagioclase-amphibole (pyroxene) layers. Maintenance of a high temperature of the melt was probably a main factor in the broad development and large crystal size observed for the innermost zones.

Growing space, another important factor for the generation of radial textures, might have been afforded by the dyke-like shape of the orbicular body. The contact zone between the recently formed country rock and the intruding melt was probably a place of concentrated fluid circulation as illustrated by the comb layering contact.

The depletion of CaO , Fe_2O_3 , MgO and Al_2O_3 in melt Σ was accompanied by a relative enrichment in SiO_2 and K_2O . Enrichment in K_2O is already reflected at the outermost zones (4 and 6) of the shell where biotite occurs as a main constituent and forms, almost by itself, one or two well developed rings (Zone 4) and all of Zone 6. At the same time, growing viscosity coupled with decreasing temperature produced a gradual reduction in grain size though the radial growth pattern was still maintained. The oxidation ratio increased and primary magnetite crystallized as an abundant phase in Zone 5. The outermost ring of biotite (Zone 6) crystallized from a K_2O rich residual melt; partial alteration of this ring by epidote and chlorite gives evidence of the activity of late phase residual fluids.

Thus, differentiation of melt Σ progressed to produce a rock very close to the composition of the matrix of the orbicular body with an oxidation ratio of 0.5. Crystallization of the porphyritic matrix characterized by large K-feldspar phenocrysts took then place although K-metasomatism as a later event could not be excluded.

The magmatic mechanism suggested can satisfactorily explain the big differences observed both petrographically and chemically between the matrix and the orbicules (core plus shell).

A final stage of alteration by late phase fluids from the matrix affected the country rock close to the contact as indicated by sericitization, chloritization, epidotization and albitization recognized at Contact 1. This phenomenon could also be a late manifestation of a more regional process as suggested by the alteration of the country rock farther away from the orbicular body.

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Appendix 1. Working Methods.

Samples were optically studied at the Department of Geology of the University of Chile in Santiago and of the University of Hokkaido in Sapporo, Japan. Modal analyses are based on 5000 point counts in one thin section. Plagioclase compositions were determined using a fouraxis universal stage following the method of Slemmons (1962); structural state of plagioclases from the core and the matrix was determined by X-ray diffraction (Smith and Yoder, 1956) at the Department of Geology of Hokkaido University. Major element analyses were done by gravimetric methods in Santiago and C.I.P.W. norms were calculated using a computer program in Hokkaido. Trace elements were determined by atomic absorption techniques at the University of Chile.

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