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Chromite Growth, Dissolution and Deformation from a Morphological View Point: SEM Investigations

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The SEM investigations on some chromite crystals show significant morphological differences between cumulate chromites (from stratiform complexes and from ophiolites) and chromites from podiform deposits (ophiolites). The later exhibit a rounded habit and abundant pits which are both the result of dissolution processes. Accordingly, the interpretation of the silicate inclusions within these chromites and the interpretation of the trace-elements distribution need great care. The nodules, a typical structure of the podiform chromites, are explained by a magmatic growth followed by a progressive recrystallization. The accessory chromites which define the mineral lineation in the tectonite peridotites from ophiolites have been deformed by processes of intracrystalline gliding, stretching and dissolution. In the harzburgites, the orthopyroxene has progressively exsolved at sub-solidus (symplektites) vermicular to massive chromite displaying euhedral forms. In the dunitic lenses, the idiomorphic chromites which are aligned parallel to the lineation may have also recrystallized in a solid state.

INTRODUCTION

The chromitite pods are characteristic of ophiolitic complexes (Thayer, 1960). They are located close to the base of the cumulates within the underlying mantle derived peridotites. They have been generally interpreted as magmatic deposits considering the ore structures (layered with disseminated, occluded silicate or chromite net textures; nodular or orbicular; massive; etc...). Two models are in competition: (1) gravitational ore segregations from the magmatic chamber in troughs upon the basement of mantle-peridotites (Borchert, 1960); (2) in-situ crystallization in magmatic pipes or chambers within the mantle-peridotites during the plastic deformation (Dickey, 1975; Juteau, 1975; Leblanc, 1978). Indeed the pods are generally elongated parallel to the lineation of the surrounding peridotites (Cassard et al., 1980) and the ores display deformation structures (pull-apart). After geochemical data (Leblanc et al., 1980), petrographical studies from chromite grains were needed in order to obtain informations on their genesis. Difficult to reconstruct from thin or polished sections, morphology and surface state of the chromite grains were observed using a Scaning

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Electronic Microscope GEOL-SSM 35. It allows magnification from 20 to 30 000 at which a few hundred Ångstroms details may be distinguished. Our main problem was to obtain small splinters of rock showing chromite grains, unbroken and with undammaged surface, in elevation over the surrounding silicates. The best samples came from slightly weathered or serpentinized peridotites. Acid etching tests on fresh peridotites removed altered silicates and were without effect on the chromites. Before observation, the samples were cleaned by ultrasounds.

We have observed many chromites from the pods and the peridotites of some ophiolites (e.g. Antalya - Turkey; Troodos - Cyprus; New Caledonia) and for comparison some chromites from the cumulates of the Bushveld complex and from the cumulates which overlie the mantle derived peridotites of the ophiolites.

OBSERVATION

1. 1. The cumulates

The chromite crystals from the mafic-ultramafic stratiform Bushveld complex (Main Chromitite Layer and Upper Chromitite Layer) are euhedral and display large, smooth and bright faces and sharp edges (Fig. 1A). Nevertheless one can observe variations between neighbouring crystals: (a) edges in elevation over flat faces; (b) sharp edges and plane faces; (c) blund edges and abundant faces. The most frequent from association is (110)(100) and accessorily (100)(111)(110). Usually the crystals are equant. The deffects are scarce (parallel lines of prismatic pits).

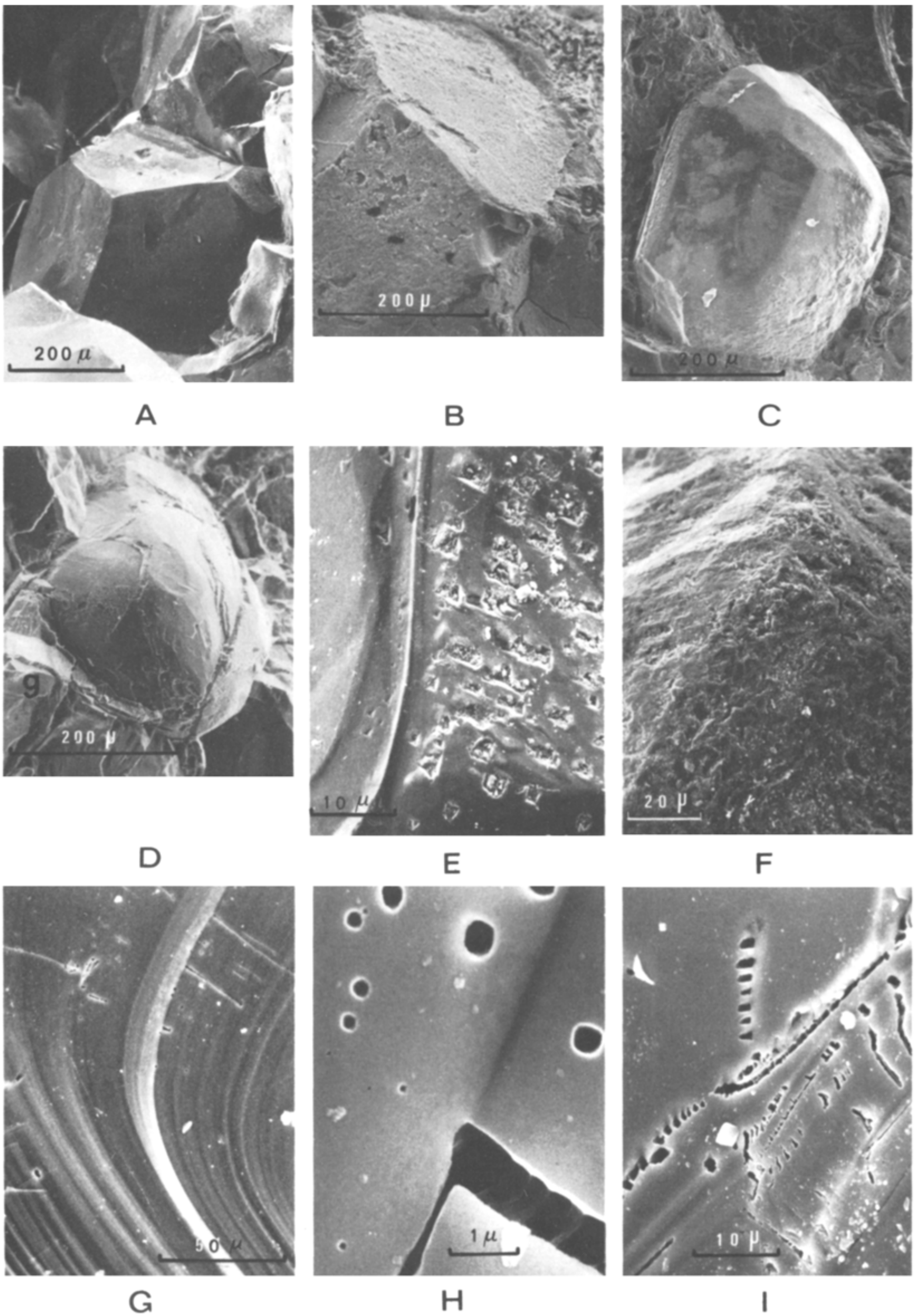
The cromite crystals from the ultramafic cumulates (base of the layered gabbros unit) of the New Caledonian ophiolitic complex display the same simple habit (Fig. 1B). Nevertheless, in comparison their edges are somewhat less sharp, their faces are dull and defects-rich. Finally, some crystals display a prismatic development and lie on their largest face.

1. 2. The podiform chromite ores

Layered, massive and nodular ores from New Caledonia, Antalya and Troodos have been investigated.

1. 2. A. The layered ores are apparently cumulate ores. They exhibit a lenticular layering on the scale of 3 to 20 millimeters. Depending on the relative proportions of chromite and olivine, the layers display disseminated, massive or intermediate structures ("chromite net" and "occluded silicates", Thayer, 1969. Nevertheless we have not found coherent evidences of gravitational deposit. On the contrary, deformation is evident considering (1) the elongation of the chromite or dunite packs and the olivine lineation which are parallel to the mineral lineation of the surrounding peridotites and (2) the associated orthogonal pull-apart lineation of the stretched chromite.

Fig. 1 A-I. SEM chromite microphotographies. A euhedral crystal of cumulus chromite (Main Chromitite Layer - critical zone, Winterveld, Bushveld). B euhedral crystal of cumulus chromite showing slight corrosion effects (olivine - chromite cumulate, Prony, New Caledonia). C D rounded crystals from layered podiform ore (C. Beyzehir, Turkey; D. Alpha, Tiebaghi, New Caledonia). E multi-facetted edge and rough face with oriented pits on a partly rounded crystal from layered podiform ore (Alpha, Tiebaghi, New Caledonia). F rounded edge with rough surface displaying numerous jagged pits on a complex grain (coalescent crystals) from layered podiform ore (GR2H, Massif du Sud, New Caledonia). G H I cleavage planes from massive podiform ore (Dyne, Massif du Sud, New Caledonia) displaying G concentric layers with tubular pits H aligned probably along dislocation planes I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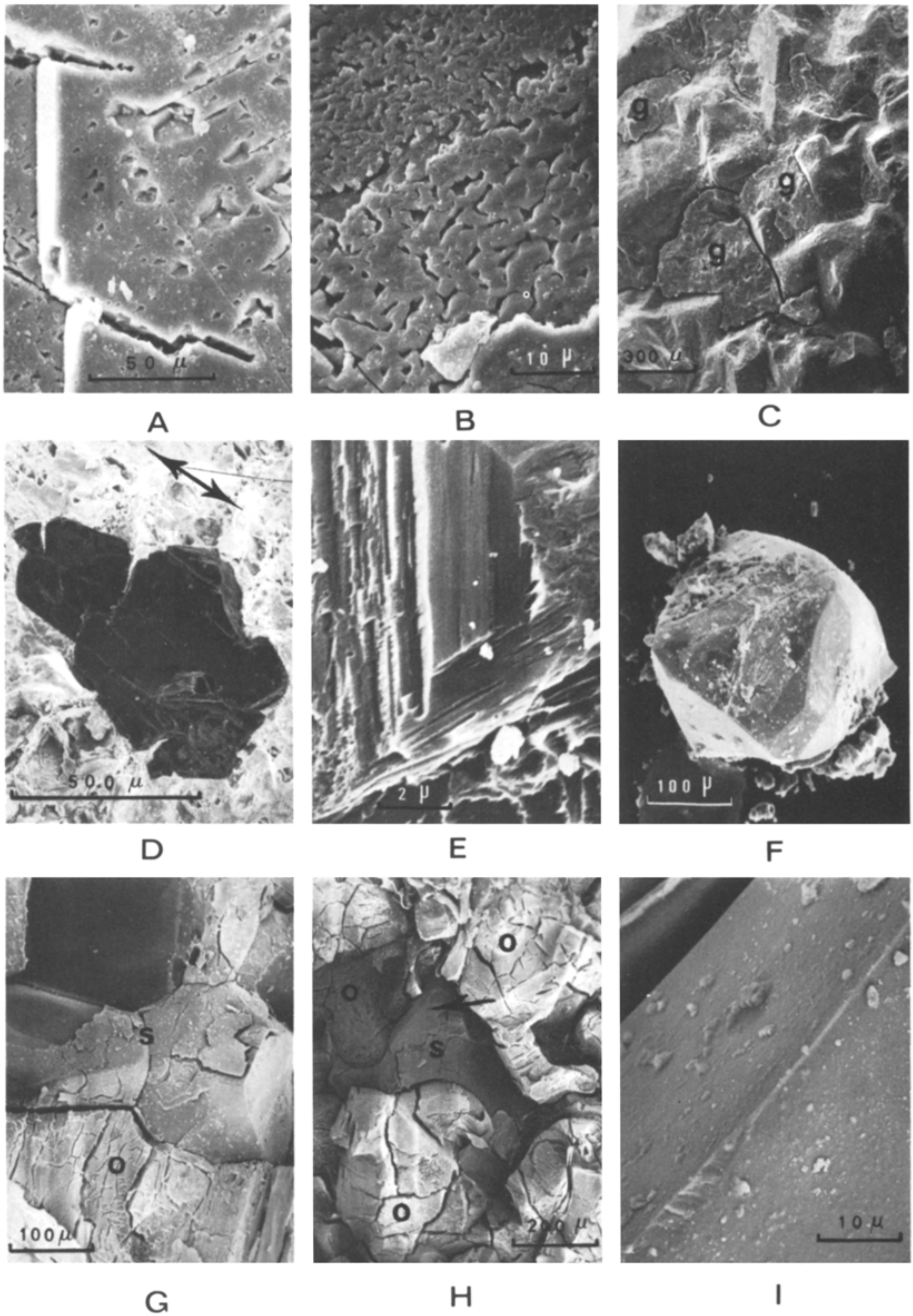
The disseminated chromite grains (0, 1 - 2 mm) are subhedral crystals with an ovoid habit (Fig. 1 C-D). They display many faces with unsharp boundaries; the edges are rounded and multifacetted (Fig. 1 E). One can observe on the same crystal (a) plane, smooth and dull faces (111)(110); (b) convex and rough faces; (c) concave faces with grooves ("gouge marks"). On the same way there are all transitions from euhedral crystals (scarce) to perfect ovoids with a dotted and ondulated surface. We have identified with difficulty the (110) (100)(111) association of faces. The dotted or rough faces are deffects-rich: prismatic oriented pits (Fig. 1 E) or abundant irregular jagged pits.

The coalescent crystals exhibit a complex assemblages of scarce crystalline faces and abundant concave ("gouge marks") or convex rough surfaces separated by rounded rough edges. Under high magnification one can observe (Fig. 1 F) a lot of irregular jagged pits (0, 5 - 1, 5 μ) upon the rough surfaces (spongiform at this scale). The pull-apart fractures are open cracks filled by serpentinized olivine. These exhibit sharp lips with a step structure.

1.2.B. The massive ores which are always in gradational contact with the other ores are locally preponderant and may constitute 5-20 m thick pods. Massive chromite ores split up readily along three orthogonal planes (100). The surface of the cleavage planes is smooth and decorated by concentric lines. These correspond to a pile of layers with concentric edges (Fig. 1 G). Under high magnification (Fig. 1 H-I) one can observe numerous tubular pits with a parallelepipedic section (0, 2 μ). Planar defects along various directions result from the progressive coalescence of the tubular pits (Fig. 1 I). Sometimes there is a lot of well oriented euhedral pits (0, 5 - 1 μ). These negative crystals are clearly connected by open cracks (Fig. 2 A). Finally (Fig. 2 B) the pits may be so abundant (30%) that the crystalline layers look like vermiculated lace with a cubic pattern (1 μ).

Moreover, the massive ores may split into large crystals (0, 5-2 cm) exhibiting an octahedral habit with roundec edges and dotted, dull and rough surfaces. These are concave or convexe and display under high magnification a sheeted structure comprizing sheets (0, 3 μ thick) along three orthogonal directions (100). Sometimes we have observed enigmatic rod structures (0, 4 μ x 0, 1 μ): chromite or fibrous serpentine gangue? In addition, a network of cubic pits (10 μ) is often observed

Fig. 2 A-I. SEM chromite microphotographies (continuation). A B cleavage plane from massive podiform ore (Vercingetorix, Massif du Sud, New Caledonia) displaying pyramidal pits aligned along open cracks A and a complex vermiculated lace B with a cubic pattern on the perpendicular plane corresponding to the surface of a large crystal (cf. text). C nodule surface (Chrome Mine, Troodos, Cyprus) exhibiting euhedral cubic forms, with blunt edges, which have the same orientation (g: residual crust of silicate gangue). D accessory chromite from a strongly deformed (tectonite) harzburgite (Kopeto, New Caledonia) lying with a lamellar habit on the foliation plane and stretched along a direction corresponding to the mineral lineation (double arrow), note the parallel slip planes and the transverse open cracks (cf. Fig. 4). E accessory chromite from a tectonite dunite (Karsanti, Turkey) displaying, under high manification, linear pits underlining the movement direction on slip planes. F accessory euhedral chromite crystal in a dunitic lense, displaying a strong chromite lineation parallel to this of the surrounding harzburgites (Massif du Sud, New Caledonia). G H I symplektite of chromite (s) within an orthopyroxene (o) from thin flat-lying network (H) to massive euhedral grains G, note I the euhedral border of H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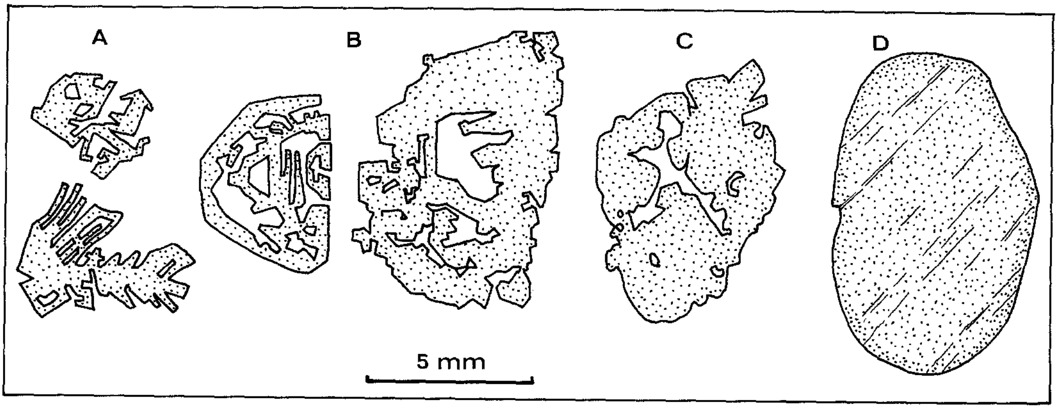

Fig. 3 A-D. Thin section drawings showing progressive evolution from skeletal chromite crystals to nodules. A skeletal crystals with christmas-tree forms (Troodos, Cyprus); B polyhedral nodules with a hollow core displaying again the chromite dendritic shape (Troodos, Cyprus); C polyhedral nodule from George Pile (New Caledonia); D massive ovoid nodule with an unique cleavage plane (Fantoche, New Caledonia)

upon the faces. These negative crystals display jagged boundaries. Finally, lenticular cavities (2 x 10 µ) are disposed en echelon along micro-cracks.

1.2.C. Nodular and orbicular ores are specific of podiform chromite deposits (Thayer, 1960). These structures are considered to have been produced (1) by the aggregation of chromite grains prior to settling (Johnston, 1936; Thayer, 1969); (2) by slumping and pellitization of settled chromite (Borchert, 1964); (3) by rapid crystallization in a supersaturated magma (Greenbaum, 1977) or from immiscible globules of chromium rich liquid (Bilgrami, 1964; McDonald, 1965).

Our observations are consistent with, and complete, the hypothesis of Greenbaum (1977): there is a continuous growth from dendritic crystals to massive nodules (Fig. 3).

1. The isolated skeletal and dentritic crystals of chromite (Troodos, Cyprus) are hollow prismatic crystals (100) with octahedral terminations (111). These display adjacent lamellae (111) giving christmas-tree forms. The main hollow prismes may be associated orthogonally. The faces are smooth, weakly ondulated, the edges are blunt without any pits.

2. Some nodules are constituted by one branched dendritic crystal well preserved in the core of the nodule with interstitial silicates (Cyprus, New Caledonia). The massive shell display a general polyhedral habit with cubic forms (100, 111, 110). Euhedral terminations on the surfaces of the nodule exhibit the (100) (110) (111) and (100) (111) form association with the same orientation (Fig. 2 C). Their edges are blunt. They are damaged by concave rough surfaces corresponding under high magnification to kinked faces with abundant (100) (110) micro-facets.

3. Common nodules are ovoid, and massive, they are elongated and flattened in a same direction. The surface is scaly and exhibits smooth pyramidal (111) forms.

4. Finally, some nodules from New Caledonia are flattened and readily splitted up along the same preferential plane. These are clearly monocrystalline. Their surface is smooth and without crystalline terminations. The pits are rare.

Our investigations on the orbicules from Antalya (Turkey) will be described in an other paper. One should note that the surface of the orbicules is similar to that of the nodules.

1.3. The disseminated chromites within the peridotites

Within the moderately deformed harzburgites the chromite appears mainly as a thin vermicular and arborescent net work on the orthopyroxene margins (symplektite texture). We have observed (Leblanc, 1978) the gradational evolution from discrete vermicules on the edges of large orthopyroxene to a massive subhedral grain surrounded by thick peduncles which occupies the major part of residual orthopyroxene. Both massive grains and vermicules display crystalline forms under high magnification (Fig. 2 G-H-I). They show smooth faces, defect-free, and sharp edges.

The strongly deformed harzburgites exhibit a chromite lineation (Darot and Boudier, 1975) within their foliation plane. The chromite grains (0, 1-0, 3 mm) have an elongated lamellar habit and lie within the foliation plane (Fig. 2 D). They display complex grain boundary shapes (Fig. 4) with an association of (100) and (111) faces. In contrast, the tips are rounded and dotted. The chromite grains are elongated, stretched and progressively disrupted (Fig. 4), with cracks perpendicular to the stretching direction. The lips of these transverse open cracks, filled by olivine, are sharp. Obliquelly it appears a system of parallel slip planes (111). These display, under high magnification, a parallel displacement with en echelon cracks. Linear pits are abundant and underline the movement direction on these planes (Fig. 2 E).

Dunite lenses and strips are common within the harzburgites. They are concordant or discordant as regards to the harzburgites foliation but display the same strong chromite lineation. These dunites are considered to be magmatic dykes or (and) a residual refractory rock resulting from the harzburgite partial melting at the border of magmatic dykes (Boudier and Nicolas, 1972). This last processus has been proposed to explain the dunite wall-rock of the chromitite pods (Leblanc, 1978; Leblanc et al., 1980). Within the dunite lenses and strips the chromite lineation is marked by parallel lines of euhedral crystals (Fig. 2 F). These exhibit numerous faces (111)(100)(110), sometimes concave, and blunt edges: an habit somewhat similar to that of the chromites from the layered ores of the pods.

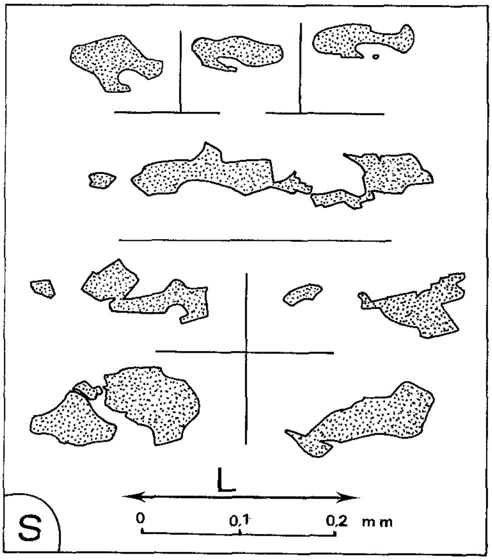

Fig. 4. Thin section drawings showing the shape of various chromite grains within the foliation plane (S) of a strongly deformed tectonite harzburgite (Kopeto, New Caledonia). Note the stretching direction parallel to the chromite lineation (L), the oblique slip planes and the disrupted grains

II. INTERPRETATION

1. The crystals displaying large, flat and smooth faces and sharp edges represent the equilibrium habit of chromite in magmatic conditions. This habit is

characteristic of the chromite crystals settled in cumulate sequences (Bushveld and ophiolite cumulates). Nevertheless we have also observed among these growth forms (edges in elevation) and dissolution forms (blunt edges). A little dissolution is attested within the chromites of the ophiolite cumulates by their dull defects-rich faces.

2. There is a tendency for the pods chromites to have a sub-spherical form. Their rounded edges, their convex and rough faces, their concave faces with grooves displaying spongious or sheeted surfaces with jagged steps are conjectured to represent the result of dissolution processes (Sunagawa, 1977). In addition, the major part of the pits might be the result of dissolution as attested by their common association with open cracks and the dissolution textures of their edges. Even euhedral orientated cavities can be formed by dissolution according to experimental works on crystal growth (Sunagawa, 1975). The lines of point-bottomed pits should probably have grown by preferential dissolution along dislocation planes. The formation of the euhedral cavities ("negative" crystals) have been directed by the crystalline structure. This does not preclude the presence of primaries "negative" crystals formed during the crystal growth but underlies the importance of dissolution in the course of natural crystallization (Authier and Zarka, 1977).

The layered ores may have originally crystallized with an euhedral habit in a magmatic stage and suffered a successive dissolution (undersaturation of the magma?). The coalescence of the grains suggests an open space moving environment (Sunagawa et al., 1975). The polycrystalline chains so-formed display a common orientation with the mineral lineation of the surrounding peridotites. The late orthogonal pull-apart cracks of the chromite were filled up by the olivine. This is in agreement with a chromite crystallization contemporaneous with a multistage plastic deformation of the peridotites.

The deformation structures are scarcely observed in the massive ores. The well developped system of cleavage planes suggests a well organized crystalline structure on a large scale. The centimetric crystals might represent the individual units of a mosaic structure resulting from secondary annealing. Evidences of dissolution are found along their grain boundaries and the cleavage planes only. The concentric structures upon these planes might be interpreted as conchoidal (break) surfaces.

We have observed a continuous growth from dendritic crystals to skeletal euhedral nodules then to massive ovoid nodules. The former were preserved (skeletal and dendritic growth habit) probably by a providential quenching of the magma. This observation and others (mutual cross-cutting of dunite dykes and massive chromite dykes, refractory dunite on the wall rock of the pods) suggest a high temperature magma ($\geqslant$ 1300°C). The overgrowth of the skeletal nodules would produce massive ovoid nodules apparently monocrystalline with one plane of cleavage well developed only. The elongation of the nodules as well as the stretching and even the boudinage of the orbicules are coeval with the plastic deformation of the peridotites (same lineation). The external crystalline structures and the contact relationship of the nodules (limp deformation or crumbling after collision) witnesses to magmatic environment. If it is the case we should propose a similar conclusion than this of Doukhan et al. (1979): a crystallization initiated in magmatic conditions followed by plastic deformation in a sub-solid state.

3. The symplektite textures of chromiferous spinel within the orthopyroxenes result from a secondary desequilibrium of the OPX during P.T. changes and proceed in solidus or sub-solidus conditions. We have noted euhedral forms and smooth faces deffect-free for massive spinel grains as well for vermicules. The interpretation of euhedral crystals of chromite needs care: these might have crystallized in magmatic conditions as

well as in solid conditions. Then the euhedral habit of the chromites from dunite lenses and strips are either magmatic products or residual refractory products re-equilibrated at sub-solidus conditions.

Finally, the chromite grains within the strongly deformed harzburgites were progressively elongated, stretched and disrupted into smaller grains. The lamellar chromite grains lies probably on (100) faces, upon the foliation plane and have been stretched by gliding along slip planes (111) and disrupted along orthogonal planes (pull-apart) with dissolution upon the tips. This stretching process results in smaller ovoid grains and involves both translation gliding (as for the silicates, Nicolas et al., 1971), mechanical disruption and dissolution processes.

CONCLUSION

1. The chromite crystals from the ophiolitic cumulates are similar to those from the Bushveld complex (euhedral crystals grown in magmatic conditions). Nevertheless the former exhibit a touch of dissolution which might result from a more open and unstable magmatic environment (Church and Riccio, 1977).

2. The podiform chromite ores display disseminated chromite crystals with a rounded habit interpreted as due to dissolution processes. The cavities and pits are abundant and many of them are clearly secondary. Accordingly, the interpretation of the inclusions needs great care with regards to the use of the included material (primary or secondary) as geothermometers and geobarometers. In the same way the interpretation of the trace elements distribution in the chromites may be falsified by the cavities content.

3. The chromite from podiform deposits have crystallized in a magmatic stage. In particulary, the chromite nodules result from an overgrowth of skeletal crystals and not from the pelletization of settled chromites. The coalescence of the grains, the orientation of some magmatic structures, the dissolution marks suggest an open space moving environment. The temperature of the magma probably exceeded 1300°C as attested by quenched structures, refractory dunite foot-wall and cross-cutting of dunite and chromite veins. The massive ores represent probably a late and large overgrowth which might have obliterated the former magmatic or tectonic structures. For Doukhan et al. (1979) the contemporaneous plastic deformation affected the chromite pods at the end of the crystallization only when the liquid phase disappeared.

These data allow up to propose the following conclusion: the chromitite pods results from a multistage crystallization of chromite in magmatic pipes or channels related to partial melting processes (Juteau, 1975) within the mantle derived peridotites subjected to a continuous plastic deformation process.

4. The chromite stretching in the harzburgites resulted both from translation gliding (111), mechanical disruption and dissolution processes coeval with solid state flow in peridotites.

5. Chromite crystallization in the solid state (e.g. symplektite) may produce euhedral crystals. Accordingly, the euhedral habit is not necessarily an evidence of magmatic crystallization but also of a strong diffusion which may be realized at sub-solidus state.

6. Finally, the microscopic investigation of the morphology and the surface state of chromite grains appears to be a plenty usefull scale of observation.

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