Mineral. Deposita 20, 290–301 (1985)

MINERALIUM DEPOSITA

Structural features of ophiolitic chromitites in the Zambales Range, Luzon, Philippines

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Abstract. The chromitite-bearing peridotites of the Zambales mafic-ultramafic complex form the lowermost level of the Zambales ophiolite, which exposes a complete ophiolitic sequence. The chromitites occur close to the peridotite/gabbro transition zone.

The chromite orebodies are structurally classified into three major types: (1) concordant tabular deposits, (2) strings of pods and (3) pocketlike deposits.

Concordant tabular deposits show a gradational transition from chromitite to host rock (modal grading) and are characterized by the parallelism of ore and host-rock structures. Primary magmatic features like inch-scale layering, size grading, glomeroporphyric chromite aggregates, skeletal chromite growth and adcumulus growth (cumulus textures) are common.

The concordant chromite bodies are often tectonically disrupted and boudined forming strings of pods or fault-controlled pocketlike deposits. With increasing tectonization chromite shows pull-apart textures and lineations (plastic deformation), shearing, prismatic jointing, brecciation and mylonitization (brittle deformation). Recrystallization of cataclastic chromite occurs on a microscopic scale.

Plastic deformation is caused by mantle flow and/or the volume increase of the peridotites during serpentinization. The influence of mantle flow is indicated by the orientation of the pod strings and lineations in chromitite perpendicular to the ridge axis. Brittle deformation of chromite (cataclasis) and disruption by faults is related to the emplacement of the ophiolite.

Introduction

Following the classification of Jackson and Thayer (1972) two major types of magmatic chromite deposits have been distinguished.

Stratiform chromite deposits are restricted to layered intrusions such as Bushveld or Stillwater. The chromitites form extensive layers, up to 1.5 m thick in certain stratigraphic levels. The layers are not deformed and display typical cumulate structures with small idiomorphic chromite crystals and larger poikilitic silicates.

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Podiform chromite deposits, however, are found in ophiolite complexes, which are interpreted as fragments of oceanic lithosphere. Ophiolites have been recognized, complete or disrupted, in Alpine-type orogenic belts and in island arcs. Generally, the podiform/ophiolitic chromite deposits are irregular in form with limited lateral extension and occur within tectonite peridotite, interpreted as depleted mantle.

Relict cumulate structures in ophiolitic chromitites have been described for various ophiolite complexes (Thayer 1969, 1970; Greenbaum 1977; Brown 1980; Burgath and Weiser 1980; Moutte 1982; Chakraborty and Chakraborty 1984; Ahmed 1984). It is now generally accepted that podiform/ophiolitic chromite deposits form by crystal fractionation and accumulation from partial melts raised at accreting plate margins.

The first models of ophiolite genesis assume a horizontally spreading asthenosphere, forming chromite cumulates as elongated tabular layers in small magma pockets (Dickey 1975) or at the flat floor of a horizontally layered, steady-state magma chamber (e.g., Greenbaum 1972). The irregular chromite pods within tectonite peridotites have been explained as being subsequently inserted by the tight folding of the magma chamber floor (Greenbaum 1977) or by gravitational sinking of the chromite layers into the plastic peridotites (Dickey 1975).

More recently, several authors have discussed a model of diapirically spreading asthenosphere (Nicolas and Violette 1982), in which a narrow vertical intrusion of partially molten peridotites feeds the crustal magma chamber and fills the gap due to spreading. This "dike-intrusion" model explains the chromite pods as having originated directly inside the peridotites. Cassard et al. (1981) and Lago et al. (1982) interpreted the chromitites as being generated by dynamic crystallization inside the channels opened in the tectonite peridotites by the rising magma.

Geologic setting of the investigated chromite deposits

Plate tectonics

The Zambales ophiolite is a part of the Philippine island-arc system. This arc represents a crustal fragment wedged between two opposing subduction zones (De Boer et al. 1980). Nearby ophiolite complexes are associated with the subduction zones.

The eastern subduction zone (Philippine trench – Quezon trench) probably originated in the Eocene during northwest-southeast spreading of the West Philippine basin.

The western subduction zone (Manila trench and Bataan orogen) originated in the Oligocene by the spreading and formation of a marginal basin, i.e., the back arc basin of the Philippine island arc, which today forms the South China Sea.

Early investigators such as Karig (1971) describe the Zambales ophiolite as a fragment of oceanic crust of the South China Sea, emplaced adjacent to the Manila trench subduction during the Oligocene. More recently, Schweller et al. (1983) and Hawkins and Evans (1983) predate the Zambales ophiolite relative to the opening of the South China Sea. Hawkins and Evans (1983) interpret the ophiolite as being derived from an island arc-back arc basin pair.

Regional geology

The Zambales Range consists predominantly of peridotites and gabbroic rocks of the Zambales ophiolite (Fig. 1), which represents a complete ophiolitic sequence including

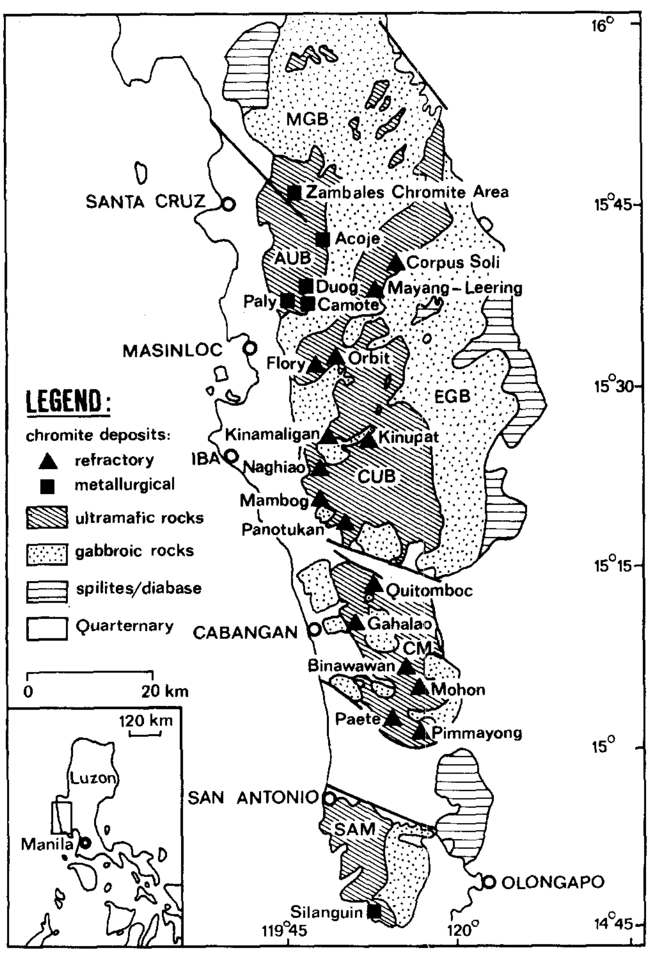

Fig. 1. Geological map and structural units of the Zambales Range and localities of investigated chromite deposits: AUB = Acoje ultramafic belt, CUB = Coto ultramafic belt, MGB = Middle gabbro belt, EGB = Eastern gabbro belt, CM = Cabangan massif, SAM = San Antonio massif

serpentinized chromitiferous peridotites, layered mafic cumulates, sheeted dikes, pillow lavas and marine sediments. Rossman (1964) refers to the peridotite-gabbro association collectively as the Zambales mafic-ultramafic complex. The complex is divided into the Masinloc massif, the Cabangan massif and the San Antonio massif (Bacuta 1978). Each of these peridotite-gabbro massifs is bordered by faults.

Fernandez (1960) proposed a further subdivision of the Masinloc massif into the Acoje ultramafic belt, which is associated with the middle gabbro belt, and the Coto ultramafic belt, which is associated with the eastern gabbro belt. Hawkins and Evans (1983) refer to the two peridotite-gabbro units, which are divided by the Lawis fault, as the Acoje block and the Coto block. They distinguish these blocks based on their crustal thickness and the geochemistry of the crust and mantle rocks. Thus, the crustal section of the Coto block reachs a thickness of approximately 5 km and originated in a back arc basin, whereas the crustal section of the Acoje block is approximately 9 km thick and originated in a nascent island arc.

Seismic reflection profiles (Schweller et al. 1983) demonstrate that the Zambales ophiolite was tilted eastward during the Miocene. The uplift and eastward tilting is believed to be related to subduction at the Manila trench.

Chromite deposits

With 62 chromite deposits the Zambales Range is the major source of chromite in the Philippines (Bacuta 1978). The geology of the chromite deposits, the regional distribution of refractory and metallurgical type ores and the geochemistry of chrome spinels in chromitites and chromitiferous rocks have been described by several authors (Stoll 1958; Fernandez 1960; Paringit 1977; Bacuta 1978, Villones et al. 1980, Friedrich et al. 1981, Leblanc and Violette 1983, Hock 1983).

Cr-rich chromite ore of the metallurgical type occurs in the Acoje ultramafic belt and in the San Antonio massif, where it is associated with a sequence of peridotite, pyroxenite and noritic gabbro (Villones et al. 1980). The chromite seams and numerous satellite chromite strings occur approximately 700–1000 m below the peridotite/norite transition zone ("petrological Moho"). The chromitite-bearing rock is predominantly dunite with interlayered harzburgite and pyroxenite.

Al-rich chromite ore of the refractory type occurs in the Coto ultramafic belt and in the Cabangan massif, where it is restricted to a sequence of peridotite, troctolite and olivine gabbro (Villones et al. 1980). The chromitite-bearing sequence occurs approximately 250–350 m below the peridotite/gabbro transition zone and consists either of harzburgite with intercalated layers of feldspatic peridotite (picrite) or lherzolite (Hock 1983).

Structural types of podiform chromite deposits

Structural features of 21 chromite deposits in Zambales (Fig. 1) have been studied by the authors; structural data are compiled in Tables 1–3. Applying the structural classification of chromite pods by Cassard et al. (1981), the chromite deposits can be divided into three types: (1) concordant tabular deposits, (2) string-of-pods deposits

Table 1. Summarized structural data of chromite deposits studied in the Acoje ultramafic belt and in the San Antonio massif (metallurgical-type chromite ores)

Deposit	A	B	C	D	E	F	G	H	I	J
Acoje mine	700–1,000	concordant tabular (2–3)	schlieren	8,000	40/5–10	30°/70°SE 160°/80°SW	dunite: 24°/72°SE norite: 26°/86°SE	70°SE	218°/50°	50°/77°NW 128°/43°SW
Camote	?	string of pods (3)	schlieren-platten	50	4.5/?	30°/20°NW	50°/? NW	?	?	52°/45°SE 135°/46°NE
Duog	?	string of pods (1)	massive	60	7.5/5	95°/80°N	107/?			39°/80°SE 116°/82°NE
Paly	?	concordant tabular	schlieren-platten	800	25/?	28°/45°SE	?	?	?	55°/40°SE 130°/60°SW
Silanguin	ca. 700	?	schlieren	1,000	?	NW/45°NE	?	?	?	52°/56°SE 140°/42°SW
Zambales chromite area	ca. 1,000	string of pods	schlieren-platten and massive	3,000	2,5/1.5	Burgos: 50°/70°NW Luna: 173°/79°E Osminia: 10°/80°E	?	?	?	18°/78°SE 135°/66°SW

A: distance to the "petrological Moho" (m)
B: shape of deposit (number of chromitite layers)
C: main ore types
D: lateral extension of mineralized zone (m)
E: maximum thickness/estimated average thickness of chromitites (m)
F: layering of chromitite (strike/dip)
G: layering of host and country rocks (strike/dip)
H: foliation in harzburgite; data after Nicolas and Violette (1982)
I: lineation in harzburgite (direction/plunge); data after Nicolas and Violette (1982)
J: most abundant local faults and joints (strike/dip)

and (3) pocketlike deposits. The classification corresponds to the increasing deformation of the chromitites.

Concordant tabular deposits

Concordant chromitites in the Acoje mine (Fig. 2) are parallel to the country-rock layering, and the ore zone can be traced along strike for at least 8 km, including the Acoje mine, Dawn mine and Aurora mine (Paringit 1977). The orebodies and their internal layering, indicated by variations in chromite/silicate ratio and grain size, are parallel to the layering of the host dunites, which is defined by satellite chromite strings and intercalated pyroxenite seams. The transition from chromitite to host dunite is characterized by the modal grading of chromite and olivine following the general scheme: massive ore at the basal contact of the orebody, "schlieren" ore, disseminated ore, chatty ore and finally dunite at the top wall. The maximum thickness of the undeformed concordant chromitites reaches approximately 10 m; tectonized chromitites close to the Acoje fault are as much as 40 m thick. The chromitites are cut and dislocated by faults (Fig. 2).

Chromitites south of the Acoje fault strike 30°NE/SW and dip 70°SE parallel to satellite chromite stringers (24°NE/SW, 72°SE), parallel to the layering of the mafic cumulates (26°NE/SW, 86°SE) and parallel to the foliation of the harzburgite dipping 70°SE (Nicolas and Violette 1982). All determined structural features of the concordant deposits at Acoje mine strike parallel to the NE/SW-striking ridge axis, which has been reconstructed by Nicolas and Violette (1982) based on the orientation of diabase dikes in the dike-swarm unit, the orientation of transform faults such as the Acoje fault and the intersection of lithologic boundaries with the magmatic accumulation plane and the plane of mineral flattening (foliation). The trend of mineral lineation in tectonite peridotites, which generally should be perpendicular to the ridge direction, is parallel to the ridge axis of the Acoje block (cf. Table 1).

Chromitites and country rocks north of the Acoje fault strike 160°NW/SE and dip 80°SW. These sequences are possibly rotated counterclockwise to the regional strike as discussed by DeBoer et al. (1980).

Strings of pods

Like the concordant deposits, the string-of-pods-type deposits occupy distinct stratigraphic positions close to the "petrological Moho". The pods range from a few tons to several 10,000 tons of chromite. Like concordant deposits, some pods show modal grading from ore to host rocks. Others are bordered by thin shear zones of flaky serpentinite. Generally, the pods are boudined or cut by faults. Some pods are folded.

Table 2. Summarized structural data of chromite deposits studied in the Coto ultramafic belt (refractory-type ores)

Deposit	A	B	C	D	E	F	G	H	I
Flory	?	single pod	massive	30	3/2.5	50°/78°SE	?	?	54°/74°SE 148°/82°NE
Kinamaligan	250–350	string of pods (5)	massive and schlieren	ca. 1,000	10/2				68°/42°SE
– daughter lode						159°/24°SW	?	316°/22°	134°/65°SW
– father lode						160°/57°SW	gabbro: 145°/52°SW dunite: 152°/50°SW	?	
– mother lode						15°/38°NW	dunite: 25°/22°SE harzbg.: 65°/63°SE	335°/25°	
– sister lode						?	?	145°/20°	
Kinupat	ca. 200	single pod	nodular and massive	25	?	?	?	?	72°/70°SE 146°/15°SW
Mambog	?	pocket-like	massive	ca. 25	?	?	?	?	48°/44°SE 140°/50°SW
Mangatarem	ca. 200	string of pods	massive and schlieren	ca. 3,000	?/2.5	?	?	?	?
Mayang-Leering	ca. 200	string of pods (2)	massive	ca. 2,000	?/2.4	125°/52°NE	?	?	40°/75°SE 132°/70°SW
Naghiao	ca. 300	tabular	massive and schlieren	500	?/1.5	55°/48°NW	?	?	35°/75°NW 146°/62°NE
Orbit	ca. 300	string of pods (2–3)	massive and schlieren	ca. 2,000	3.6/2	50°/45°SE	?	?	?
Panotukan	ca. 200	single pod	schlieren and chatty	20	?	115°/83°SE	?	?	60°/30°SE 89°/69°S

A: distance to the "petrological Moho" (m); B: shape of the deposit (number of chromitite layers); C: main ore types; D: lateral extension of mineralized zone (m); E: maximum thickness/estimated average thickness of chromitites (m); F: layering of chromitite (strike/dip); G: layering of host and country rocks (strike/dip); H: lineation in chromitite (direction/plunge); I: most abundant local faults and joints (strike/dip)

Table 3. Summarized structural data of chromite deposits studied in the Cabangan massif (refractory-type ores)

Deposit	A	B	C	D	E	F	G
Binawawan	?	single tabular pod	massive	41	min. 1.5	30°/?	50°/78°NW 147°/23°SW
Gahalao	ca. 200	pocketlike	massive	40	max. 10	156°/38°SW	46°/73°SE 160°/74°SW
Mohon	?	single tabular pod	massive and leopard	50	ca. 1	128°/86°NE	53°/75°SE 170°/80°W
Paete	?	pocketlike	massive and knobby	25	ca. 8	164°/61°SW	82°/72°S 173°/48°W
Pimmayong	?	pocketlike	massive and schlieren	20	min. 1.5	134°/21°NE	126°/19°NE
Quitomboc	?	single tabular pod	massive and schlieren	50	ca. 1	132°/78°NE	31°/86°SE 125°/70°NE

A: distance to the "petrological Moho" (m)
B: shape of the deposit
C: main ore types
D: lateral extension of the mineralized zone (m)
E: approximate thickness of the chromitites (m)
F: layering of the chromitite (strike/dip)
G: most abundant local faults and joints (strike/dip)

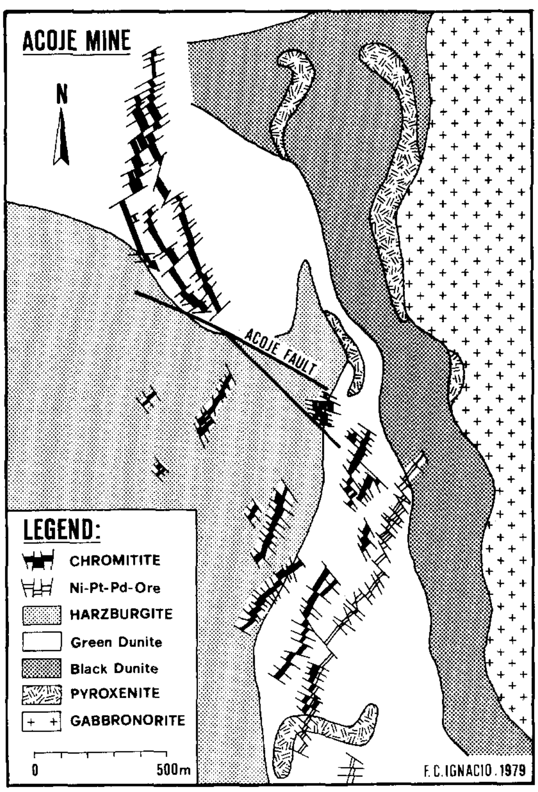

Fig. 2. Geological map of the Acoje area with a projection of subsurficially mined chromite orebodies on to the surface geology; modified after Ignacio (1979)

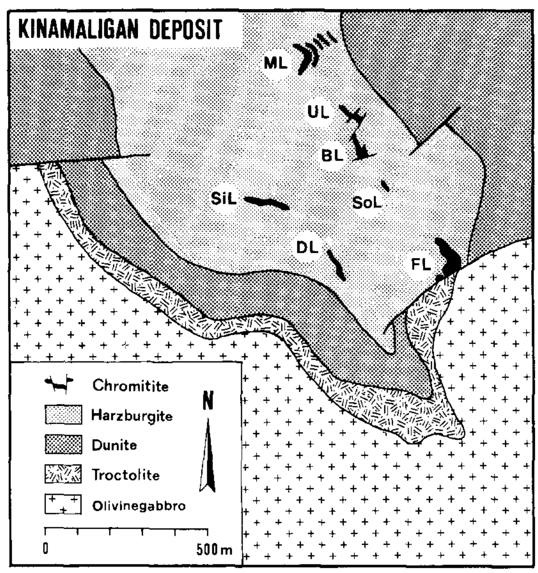

Fig. 3. Geological map of Kinamaligan deposit; five chromitite layers are traced in outcrops at the mother lode and are documented by drillings (profiles in Fontanos and Obias, 1960): BL=brother lode, DL=daughter lode (see Fig. 4), FL=father lode, ML=mother lode (see Fig. 5), SiL=sister lode, SoL=son lode, UL=uncle lode

The Kinamaligan deposit in the ultramafic belt of Coto is a representative example of this type of deposit and has two parallel strings, which strike NW/SE perpendicular to the NE/SW-striking ridge axis of the Coto block as determined by Nicolas and Violette (1982). The chromite pods occur within five stratigraphic levels of the harzburgitic host rocks (Fig. 3), oriented parallel to the layering of the host rocks, which is indicated by cm-thick layers of chromite in dunite or clinopyroxenite seams in harzburgite, and parallel to the layering in the olivine gabbros (Table 2). The outline and internal structure of single pods from Kinamaligan deposit is highly irregular (Figs. 4 and 5). Lineations in chromitite are shown by elongated chromite aggregates of leopard ores and by spindle-shaped (fusiform) lenses of disseminated ore in massive chromitites. The lineations dipping 20–25°NW are parallel to the orientation of the strings and perpendicular to the ridge axis, thus indicating the influence of mantle flow that caused the boudinaging of the pods.

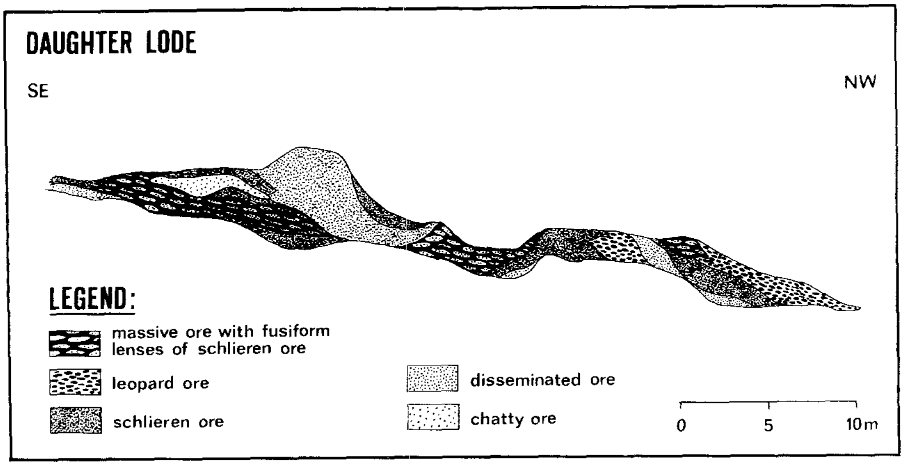

Fig. 4. Geological profile and distribution of ore types in the daughter lode orebody, of the Kinamaligan deposit; signatures indicate the orientation of both fusiform lenses in massive ore and chromite aggregates in leopard ore

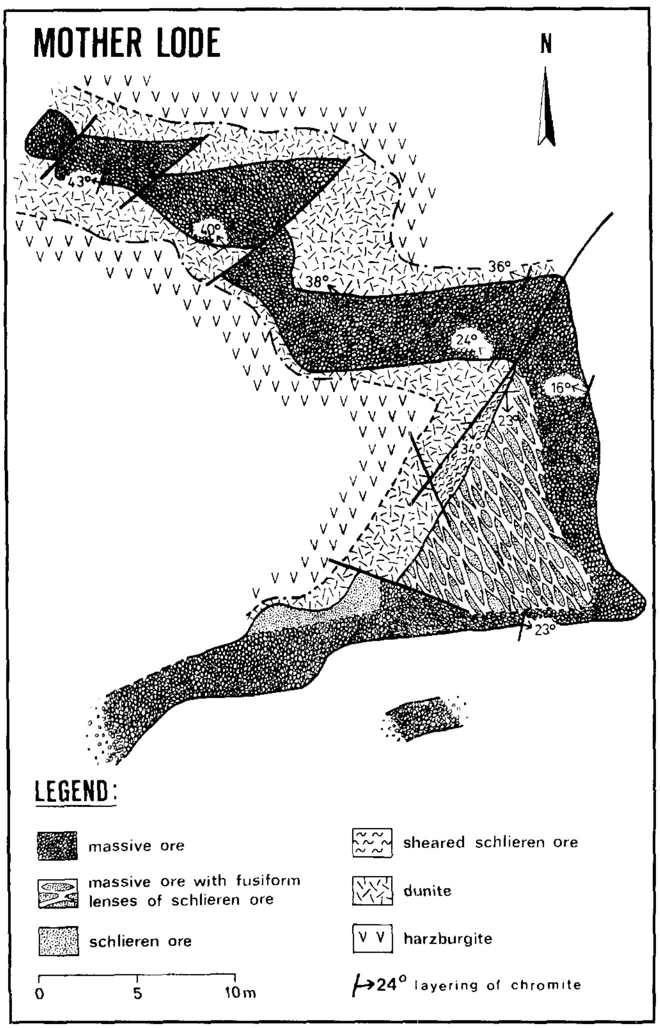

Fig. 5. Geological map and distribution of ore types in the layer 1 orebody, mother lode of the Kinamaligan deposit; signature indicates the orientation of fusiform lenses in massive ore

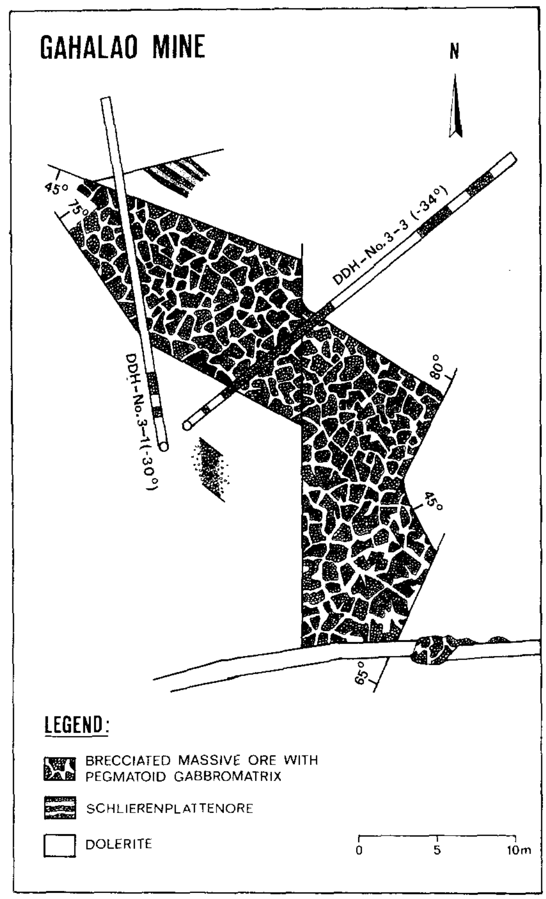

Fig. 6. Geological map of Gahalao mine and projection of drill holes DDH No. 3-1 and DDH No. 3-3; host rocks are extremely brecciated dunites and harzburgites; modified after F.S. Rubia, Golden River Mining Co. (1980)

Pocketlike deposits

Pocketlike deposits have faulted contacts, and the form of the chromite pods is controlled by the direction of the most abundant fault system. Some chromite pods are rotated relative to the regional strike of their host rocks. Chromitites and host rocks are brecciated or mylonized. These cataclastic massive ores commonly contain secondary chrome-bearing minerals like uwarovite, smaragdite or kaemmererite.

The harzburgite-hosted orebody of the Gahalao mine in the Cabangan massif is a representative example for pocketlike deposits (Fig. 6). The chromite ore is brecciated, filled with smaragdite, and crosscut by pegmatoid gabbro dikes defining a net structure. The gabbro dikes did not intrude the host harzburgite and thus are assumed to represent the mobilized silicate matrix of the primary chromite cumulates.

Ore types

Macroscopically the chromitites can be divided into massive, layered, nodular, antinodular, "schlieren" and disseminated ore.

Massive ore consists of more than 70 vol.% chromite with interstitial olivine (serpentine), pyroxenes, plagioclase (mostly altered to amorphous silica) and secondary chrome minerals.

Layered types include "schlierenplatten" ore and banded ore. Schlierenplatten ore is characterized by interlayered disseminated ore and thin dunite layers (Fig. 7 a) or by fine-grained chromite-rich seams grading to olivine-dominated layers with large hypidiomorphic olivine crystals (Fig. 7 b). Banded ore, occasionally with cross-bedding, shows inch-scale layering (Fig. 7 c). Layered ore is most abundant in concordant tabular deposits and represents typical cumulus textures.

The nodular type includes globular ore, leopard ore and knobby ore. Globular ore (Fig. 7 d) shows well-rounded chromite globules up to 4 cm in diameter with internal concentric layers. The matrix consists of plagioclase, idiomorphic pyroxenes and clusters of small idiomorphic chromite grains. Leopard ore (Fig. 7 e) is formed by oriented, spindle-shaped chromite aggregates with internal cumulus texture and massive chromite rims within a serpentine matrix. Knobby ore (Figs. 7 f and 8 a) contains octahedral chromite aggregates of 0.5–1 cm in diameter.

Antinodular ore displays hypidiomorphic olivines or olivine aggregates of max. 1 cm in diameter with small interstitial chromite crystals (Fig. 8 d).

Schlieren ore (ca. 40–70 vol% chromite) with (Fig. 8 b) or without glomeroporphyric chromite aggregates is characterized by pull-apart textures as described by Thayer (1962).

Disseminated ore (Fig. 8 c) contains 10–40 vol.% chromite, mostly xenomorphic chromite crystals less than 1 mm in diameter, whereas chatty ore (5–10 vol.% chromite) often contains large (1–3 mm in diameter) and occasionally idiomorphic (octahedral) chromite crystals.

Microstructures of the chromitites

Concordant deposits are mainly characterized by primary magmatic features, whereas tectonic deformation is evident in chromite ore from string-of-pods or pocketlike deposits.

Primary magmatic features

The observed primary magmatic features are typical cumulus textures representing different stages of chromite growth. Initial stages are chilled eutectic systems between chromite and coexisting silicates and skeletal growth of chromite. Adcumulus growth is represented by mesocumulates and adcumulates.

Chilled eutectic systems are common in schlieren-disseminated ores of the Quitomboc deposit (Fig. 9 a). Hypidiomorphic to idiomorphic chromite grains are enclosed by a rim of pyroxene containing vermiform chromites ("fingerprint" chromite).

Skeletal growth of chromites, as described by Leblanc (1980), was ascertained in schlieren ores of the Panotukan area (Fig. 9 b). Skeletal textures in chromitites from the Troodos complex are interpreted as indicators for rapid crystallization possibly due to supersaturation processes (Greenbaum 1977).

Cumulate textures are the most common primary magmatic feature of the Zambales chromitites. Layered chromitites (Figs. 7 a–c) and glomeroporphyric chromite aggregates (Fig. 8 b) are macroscopically visible cumulus textures. According to the classification of Wager et al. (1960) and Jackson (1971) the chromite-rich cumulates can be distinguished as chromite-olivine orthocumulates, chromite mesocumulates and chromite adcumulates.

Chromite-olivine orthocumulates consist of idiomorphic chromite grains in an olivine/serpentine matrix. The chromites in these orthocumulates commonly contain numerous droplike or idiomorphic inclusions of olivine and phlogopite (Fig. 9 c) or pyroxenes.

Chromite mesocumulates are characterized by a mosaic texture of idiomorphic chromites and interstitial olivine (Fig. 9 d). Interstices in Al-rich (refractory-type) chromitites are filled with plagioclase, which is often altered to amorphous silica.

Chromite adcumulate (Fig. 9 e) consists of chromite megablasts up to 8 mm in diameter. Individual chromite grains are often merged to a compound texture of chromite with small silicate interstices.

Zoned chromite (Fig. 9 f), which might represent a final stage of adcumulus growth, shows several increasingly iron-rich rims and decreasingly magnesium-rich outer rims (microprobe analysis), indicating decreasing temperatures during crystallization. The chrome and aluminium contents of the younger rims and the core are identical.

Postmagmatic deformation

The degree of deformation is dependent on the chromite/silicate ratio of the chromitites. Silicate-rich ore shows evidence of plastic deformation, commonly as pull-apart textures with irregular cracks in chromite and other tensional features such as elongated chromite aggregates of leopard ores (Fig. 7 e) and fusiform lenses of disseminated ore in massive chromitite (cf. Figs. 4 and 5). The fusiform lenses are elongated parallel to the line connecting the pods of one string and are an obvious guide to more chromite reserves of this type. Massive ore is typically deformed by brittle processes, and shows – with increasing deformation – shearing, prismatic jointing, brecciation and mylonitization.

Deformed chromite individuals with irregular cracks, which are filled with serpentine minerals, are typical pull-apart textures as described by Thayer (1962). These pull-apart textures without preferred orientation indicate a volume increase of the silicates that can be associated with the serpentinization of olivine. The described texture is typical for schlieren and schlierenplatten ore and occurs in

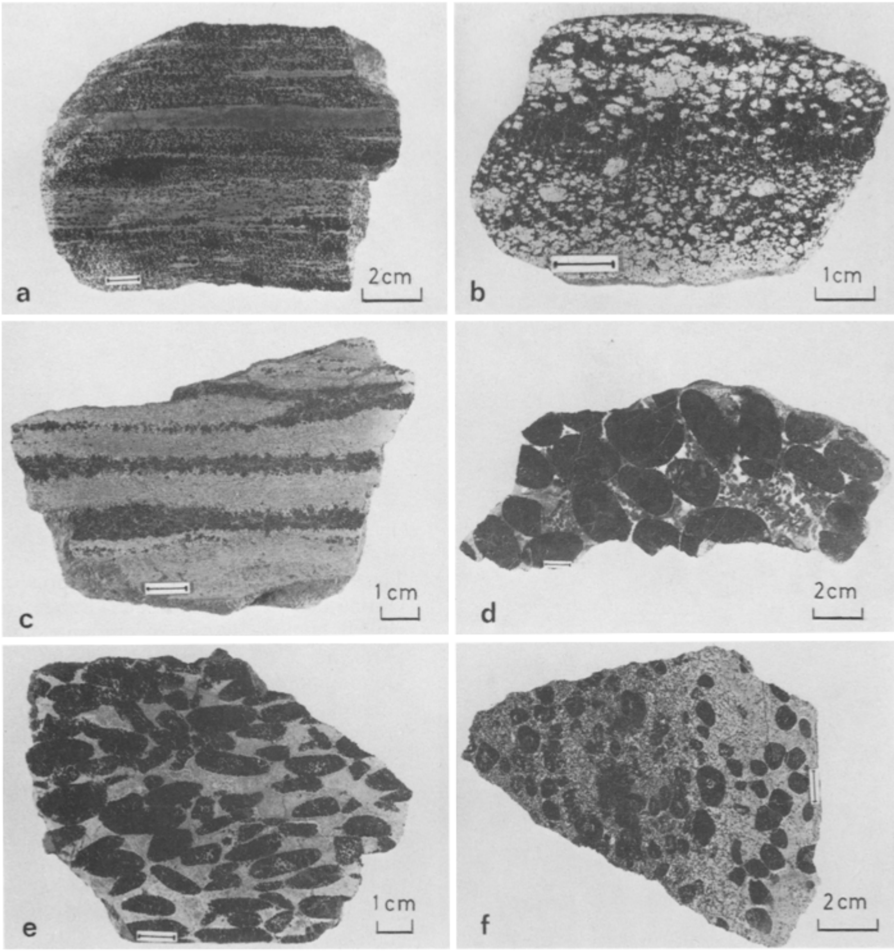

Fig. 7a–f. Layered and nodular ore types in the Zambales Range: **a** Schlierenplatten ore with interstratification of disseminations and dunite; Zambales chromite area. **b** Schlierenplatten ore with modal grading and size grading of chromite and olivine; Orbit mine. **c** Banded ore with inch-scale layering; Mayang-Leering claims. **d** Globular ore with matrix of plagioclase and idiomorphic pyroxenes; Kinupat deposit. **e** Leopard ore with internal cumulus texture of chromite aggregates; Mohon deposit. **f** Knobby ore (octahedral chromite aggregates), weakly layered with transitions to nodular ore and disseminated ore; Mambog deposit

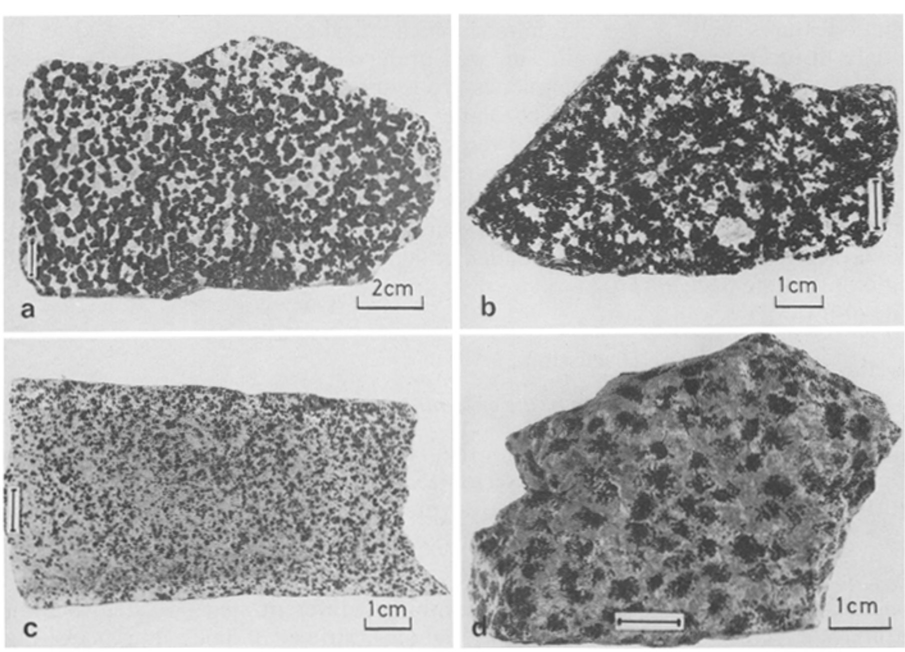

Fig. 8a–d. Antinodular and disseminated ore types of the Zambales Range: **a** Knobby ore with octahedral chromite aggregates; Paete mine. **b** Schlieren-disseminated ore with glomeroporphyric chromite aggregates; Quitomboc deposit. **c** Disseminated ore, Kinamaligan deposit. **d** Antinodular ore with hypidiomorphic olivines and interstitial chromite (spotted ore); Silanguin deposit

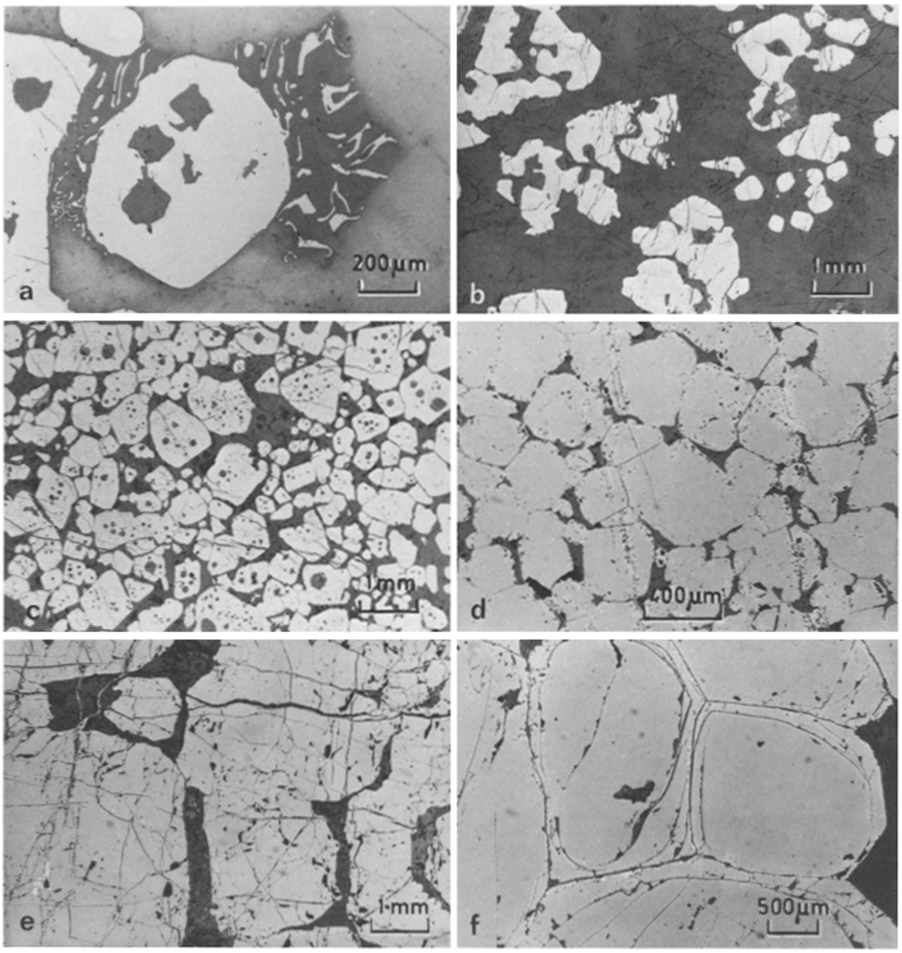

Fig. 9a–f. Primary magmatic features of chromitites in the Zambales Range: **a** chilled eutectic system of chromite and pyroxene ("fingerprint" chromite); Quitomboc deposit. **b** Skeletal chromite; Panotukan area. **c** Chromite-olivine orthocumulate with inclusions of phlogopite and serpentinized olivine in chromite; Binawawan deposit. **d** Chromite-plagioclase mesocumulate; Binawawan deposit. **e** Chromite adcumulate with chromite megacrysts; interstitial serpentine and tension fractures; Mambog deposit. **f** Zoned chromite crystals; Gahalao deposit

concordant tabular deposits as well as in the string-of-pods-type or pocketlike deposits.

Shearing of the chromitites (Fig. 10a) is observed in concordant tabular deposits as well as in the string-of-pods-type deposits. A first generation of shearing planes occurs parallel to the layering of the chromitites. Sheared chromite ores still exhibit primary magmatic features such as chromite orthocumulates, which are only disturbed by subparallel cracks.

Prismatic jointing (Fig. 10b) is the result of a second generation of shearing planes parallel to the local faults, which crosscut the orebodies almost perpendicular to the layering plane.

Brecciation (Fig. 10c) is most abundant in pocketlike deposits, which are rotated relative to the layering of their host rocks. These chromite clasts are commonly cemented by the chrome-bearing silicates smaragdite or uwarovite.

Mylonitization (Fig. 10d) is abundant in extremely tectonized pocketlike deposits such as the Pimmayong deposit. Macroscopically, these friable ores are brown. The mylonized ore contains relicts of the sheared chromite (porphyroclastic texture). The mylonites are cemented with kaemmererite.

Recrystallization

Indications of recrystallized chromite are extremely rare and sparsely documented in the literature, e.g., Ghisler (1976). Chromite mylonites from the Pimmayong deposit tend to anneal (Fig. 10e). Textures from the father lode of the Kinamaligan deposit, with slightly fractured but idiomorphic chromite grains and interstitial crushed chromite and idiomorphic uwarovite (Fig. 10f), could be interpreted as fully recrystallized chromitites. Microprobe analyses of this chromite show chemical composition identical to the chromite in well-preserved chromite-olivine-plagioclase orthocumulates from the same orebody, whereas more iron-rich chromites would be expected as the result of low temperature recrystallization. The observed chromegarnet does not indicate as high a metamorphic temperature as is considered necessary for the recrystallization of chromite. Jagitsch (1956) synthesized uwarovite from 3 $CaO+Cr_2O_3+3\,SiO_2$ under rather low pT conditions (525 °C and 110 atm).

Discussion

Origin of the chromite deposits

According to the classification of Jackson and Thayer (1972) the tectonized ophiolitic chromitites in the Zambales Range are typical podiform chromite deposits, but in two major aspects resemble structural features of stratiform chromitites:

1. Chromitites exhibiting different stages of deformation, i.e., concordant tabular, strings of pods and pocketlike

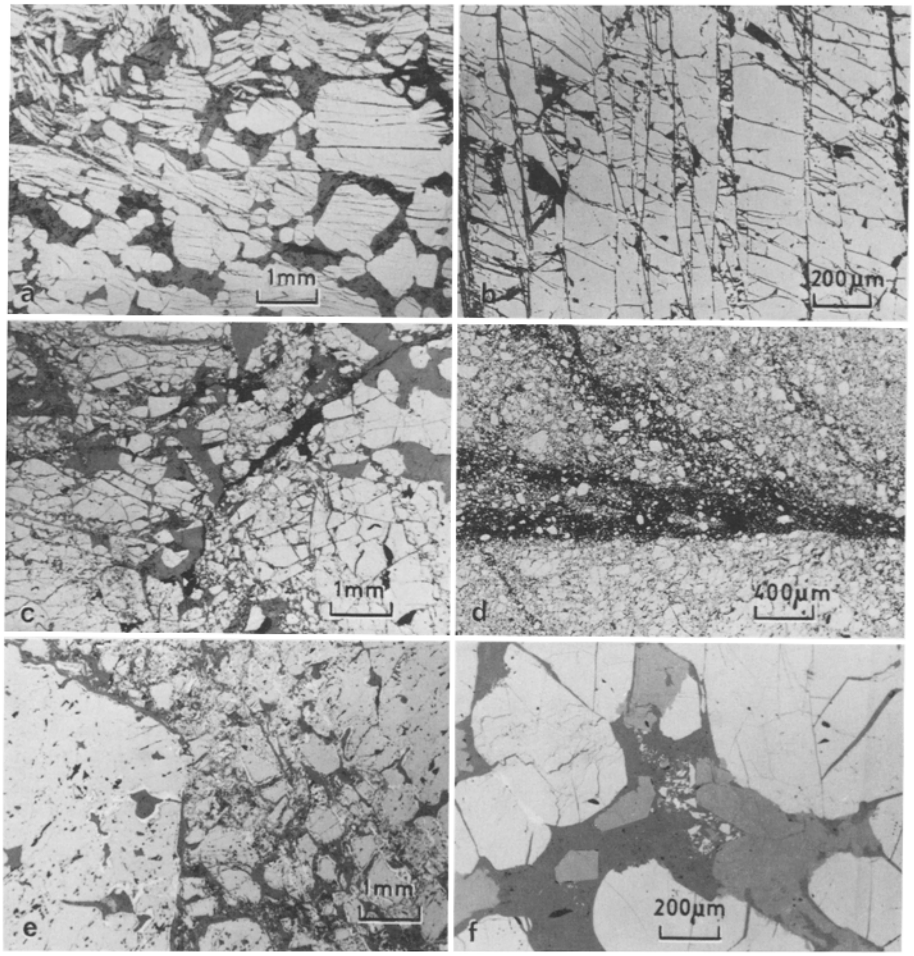

Fig. 10a–f. Postmagmatic deformation and recrystallization of chromitites in the Zambales Range: **a** Sheared chromite-olivine-plagioclase orthocumulate, single chromite grains are rotated; Kinamaligan deposit. **b** Prismatic jointing; Duog deposit. **c** Brecciated chromitite with smaragdite matrix; Orbit mine. **d** chromite mylonite with kaemmererite matrix; Darahig deposit, Samar. **e** Weakly recrystallized chromite mylonite; Pimmayong deposit. **f** Recrystallized (?) chromitite with interstitial crushed chromite and idiomorphic uwarovite; Kinamaligan deposit

deposits, all occur within the same distinct lithologic units that occupy well-defined stratigraphic positions within the magmatic sequence.
2. The chromitites are cumulates in origin, which formed as concordant tabular layers, oriented parallel to the layering of their host and country rocks.

Regarding the origin of podiform/ophiolitic chromitites there is a general contradiction between relict cumulus structures of the chromitites and the tectonite fabric and geochemistry of their host rocks, which are interpreted as depleted mantle. Thus, many authors explained the chromitites as being subsequently inserted into the tectonite peridotites. The dike-intrusion model (Nicolas and Violette 1982; Lago et al. 1982) or the idea of concordant "minichambers" (Neary and Brown 1979) are the first attempts to explain the chromite mineralizations as being generated directly inside the depleted mantle peridotites. The tectonized and serpentinized peridotites of the Zambales ophiolite however locally preserve cumulate textures of olivine (Hock 1983). Cumulate origin of the mantle sequence is also indicated by thin layers of clinopyroxenite in dunite and harzburgite and by seams of olivinegabbro in feldspathic peridotites as described by Hock (1983). The layering of the concordant tabular deposits, the layering and foliation of their ultramafic host rocks and the layering of the mafic cumulates in the lowest crust are parallel (cf. Table 1 and Fig. 2), suggesting that chromitites, host and country rocks are syngenetic cumulates, crystallized from a single, horizontally layered magma chamber. Steeply dipping chromitites can be easily explained by tilting as described for the Acoje block by Hawkins and Evans (1983) and Schweller et al. (1983). Nicolas and Violette (1982) however believe that the ophiolite massifs in Zambales have not been significantly tilted and explain steep dipping chromitites by large-scale folds.

Interpreting the chromitites in Zambales as in situ cumulates, all irregular chromite mineralizations must be explained as being formed by postmagmatic deformation as suggested for chromite deposits in the Oman Ophiolite by Christiansen (1982).

Postmagmatic deformation can be divided into plastic deformation and brittle deformation. Plastic deformation is caused by mantle flow and/or the volume increase of the peridotites during serpentinization. Brittle deformation is the result of shearing and faulting during and after emplacement of the ophiolite.

The influence of mantle flow is indicated by the orientation of strings of pods and small-scale tensional features such as elongated chromite aggregates in leopard ores and fusiform lenses in massive ores. These elongations are typical for boudined chromitites (string-of-pods-type deposits) and strike NW/SE almost perpendicular to the ridge direction, as deduced by the structural analysis of Nicolas and Violette (1982). The internal layering of these string-of-pods-type chromitites is still parallel to the layering of their host and country rocks (Table 2). Thus, mantle flow might be the major process forming string-of-pods-type deposits from concordant tabular mineralizations.

The serpentinization, possibly linked with the emplacement of the ophiolite, influences the chromitites by the volume increase of their host peridotites as discussed by Thayer (1966). The volume increase of totally serpentinized dunites can reach as much as 40 vol.%. Especially chromite layers with low olivine contents (massive ores) are boudined, whereas olivine-rich chromitites show merely pull apart textures without preferred orientation, which are typical for schlieren ore.

Fault systems developed during the emplacement of the ophiolite cut concordant deposits as well as strings of pods and caused shearing and prismatic jointing of the chromite ores. Finally, the rotation of single chromite pods, possibly adjacent to the counterclockwise rotation of the Zambales Range as discussed by DeBoer et al. (1980) causes brecciation and mylonitization, which are ubiquitous in pocketlike deposits.

Exploration and mining guides

The well-defined stratigraphic position of chromitites close to the peridotite/gabbro transitional zone ("petrological Moho") has been recognized in many ophiolite complexes (e.g., Thayer 1964) and is considered a useful guide in prospecting for chromite on a regional scale.

The orientation of pod strings and lineations in the chromitites perpendicular to the ridge axis is obviously a guide to more chromite reserves of this type in a certain mining district. The two most abundant joint systems strike almost parallel and perpendicular to the layering of the chromitites (see Tables 1–3) and might be helpful in determining the general orientation of the mineralized zone, especially in areas covered with rain forests as in Zambales.

The most important exploration and mining guide, however, is the relationship between ore types and ore qualities, deposit type and tonnage.

Concordant tabular deposits are the most continous mineralizations, disrupted only by faults. This type of mineralization has generally been slightly influenced by deformation and therefore is easily exploited. Concordant tabular deposits have the highest tonnage (Table 4) but commonly consist of layered schlierenplatten ore and disseminations and thus need an upgrading plant, which produces chromite concentrates (fines).

Tonnages of the string-of-pods deposits are lower than concordant tabular deposits (Table 4), caused by limited lateral extensions due to boudinages. The ore types within each mining district are highly variable, but massive ores are more abundant than in concordant tabular deposits. In the Zambales Range hard lumpy ores are obtained by handpicking as an upgrading method predominantly in this type of mineralization.

Pocketlike deposits contain extremely silicate-poor, brecciated massive ores (friables). Pocketlike deposits contain the lowest tonnages (Table 4).

Table 4. Chromite ore reserves of some investigated chromite deposits in the Zambales Range; quoted tonnages of Acoje mine reflect explored reserves in 1975, others are total reserves

Deposit Type/Mine	Reserves	Reference
Concordant tabular		
Acoje mine	1,4 Mio t	Acoje Mining Co. (1975)
String of pods		
Kinamaligan deposit	200,700 t	Fontanos and Obias (1960)
Mangatarem Corpus Soli	340,000 t	Benguet Consolidated (1980)
Orbit mine	407,000 t	Dolino and Aleria (1976)
Zambales Chromite Area	166,000 t	Wolff (1978)
Pocketlike		
Naghiao deposit	75,000 t	McPhar Geoservices (1980)
Paete mine	41,000 t	Amerasia Mining Co. (1980)

Acknowledgements. The research project on chromite deposits in Zambales has been supported by the German Ministry of Research and Technology (BMFT-Project 03 R-214/3) and performed in cooperation with Metallgesellschaft AG, Frankfurt. The authors wish to thank Dr. C.M. Düsing from the Metallgesellschaft Manila in particular for supporting and organizing the field investigations. We also wish to thank the Philippine mining companies supporting our studies, especially Mr. J.A. Vinco, manager of Pulsar Minerals, mining engineer F.S. Rubia from Golden River Mining Corp., mining engineer S. Omagtang from Amerasia Mining and Development Corp. and the staff from the Geology and Exploration Department of Acoje Mining Co. Inc. Our thanks are also due to Dr. H. Prichard from Open University, Milton Keynes, England and Mr. F.G. Christiansen from the Geological Survey of Greenland, Copenhagen, Denmark, for critical comments on the paper.

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Received: November 6, 1984
Accepted: May 20, 1985