GREENSTONES AS A PART OF THE MINAS SUPERGROUP IN THE QUADRILÁTERO FERRÍFERO, MINAS GERAIS, BRAZIL

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ABSTRACT A sequence of greenstones derived from the low-grade metamorphism of mafic and ultramafic rocks has been recognized within the Middle Precambrian Minas Group (or Supergroup), encompassing the main iron formation unit (itabirite). The greenstone sequence, which is conspicuously distributed in the Moeda and Dom Bosco Synclines occur characteristically within the Batatal and Gandarela Formations. Cross-sections along the Moeda and Dom Bosco Synclines have demonstrated the relative position of the greenstones within the Minas Unit, as well as the stratigraphic situation of the dolomite lenses (with stromatolites) within the Gandarela Formation. Previous works (Guimarães, 1951 and 1964) suggested a strong affinity between the Minas iron formation and metavolcanic rocks, while others (Dorr, 1969) pointed out a shallow and restricted sea without any volcanic contribution to form the itabirite and all the Minas sequence. However, recent researches have shown the existence of greenstones in the upper part of the Batatal Formation (as previously indicated by Harder & Chamberlin, 1915) and in the lower part of the Gandarela Formation. Chemical analysis of greenstones, petrographic work, and trace element (Ti, Cr, V, Ni, and Co) content from magnetites of the greenstones revealed a mafic and ultramafic affiliation.

RESUMO Uma sequência de *greenstones* derivados de metamorfismo de baixo grau, de rochas máficas e ultramáficas, foi identificada no Supergupo Minas, Quadrilátero Ferrífero, envolvendo a formação ferrífera principal composta de itabiritos. A sequência de *greenstones*, que é caracteristicamente distribuída nos sinclinais Moeda e Dom Bosco, ocorre como parte das formações Batatal e Gandarela. Seções geológicas ao longo daquelas estruturas demonstraram a posição relativa dos *greenstones* dentro do Supergupo Minas, tanto quanto a situação estratigráfica das lentes dolomíticas (com estromatólitos) na Formação Gandarela. Trabalhos anteriores (Guimarães, 1951 e 1964) têm sugerido uma forte afinidade entre a formação ferrífera Minas e rochas metavulcânicas, enquanto outros (Dorr, 1969) têm indicado um ambiente deposicional de mares rasos e restritos sem qualquer contribuição vulcânica para formar o itabirito e a sequência Minas. Entretanto pesquisadores recentes têm mostrado a existência de *greenstones* na parte superior da Formação Batatal e na parte inferior da Formação Gandarela. Análises químicas dos *greenstones*, petrografia e elementos-traço (Ni, Cr, V, Ti e Co) em magnetitas dos *greenstones* revelaram afiliações máficas e ultramáficas para as rochas.

INTRODUCTION The main purpose of the present study is to point out the existence of greenstone sequences within the Batatal and Gandarela Formation, as well as to describe the mutual litho-stratigraphic relationships between the greenstones and the Cauê Itabirite (iron formation) in the Moeda and Dom Bosco Synclines, in the Quadrilátero Ferrífero. Recent field and petrographic data together with bulk chemical analysis and trace element content in magnetites from the Batatal and Gandarela greenstones conflict and contrast with previous reports, such as Dorr (1969) who postulated the absence of volcanic rocks within the Minas Supergroup in the Quadrilátero Ferrífero. The presence of volcanic rocks within the Minas sequence has been frequently reported by Guimarães (1935, 1951 and 1964), Guild (1957) and Johnson (1962).

Harder and Chamberlin (1915) described "a sheet of serpentinized eruptive rock" resting upon the Batatal schist and at the base of the iron formation, later considered as uncertain relative age by Maxwell (1972). Previously, Simmons (1968) suggested that these mafic rocks would be intrusive in the Rio das Velhas Series. Guimarães (1951) included serpentinites, talc-schists, chlorite-schists, derived from submarine

basaltic volcanism, and dolomites within the middle unit of the Minas Series together with iron formation, but these rock successions were demonstrated to represent pre-Minas or Rio das Velhas Series (Dorr *et al.* 1957). Johnson (1962) described "greenstones of possible volcanic origin within the Gandarela Formation found in two exposures at Dom Bosco Quadrangle" and Guild (1957) described volcanic material in the Minas Series at Congonhas Quadrangle. Nevertheless Dorr (1969) suggested that the Batatal, Cauê Itabirite and Gandarela Formations correspond to sediments deposited in a stable-shelf environment without any volcanic contributions except in the Sabará Formation.

Recent field work done by this author confirmed the existence of the greenstones, depicted by the cross sections through Serras da Mutuca, Saboeiro, Moeda in the hills on the northern part of the Dom Bosco Syncline (Fig. 1). Bulk chemical analysis, petrographic work and trace element (Ni, Cr, V, Ti, and Co) analysis in magnetites from the greenstones strongly suggest an ultramafic to mafic affiliation for both the Batatal and Gandarela greenstones. This paper evaluates and compares the composition of the Minas greenstones with some described elsewhere.

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Figure 1 — Dolomite distribution in the Curral Anticline, Moeda and Dom Bosco Synclines. Observe sample and section locations

BATATAL GREENSTONES The Batatal formation consists of twofold subdivision (Fig. 2); the lowermost boron potassic aluminous schist composed of muscovite sericite schist, locally with basal breccia and quartzite bands and black, fine-grained, tourmalinite layers and lenses, boudinaged and locally interbedded upwards with thin dolomite lenses as at Minas da Passagem gold mine (Fleischer and Routhier, 1973). The uppermost (greenstone-rich unit) comprises a sequence of mafic greenstones, mainly metabasites, laminated kaolinitic mafic rock, talc schist, thin dolomite lenses within greenschist, and beds of yellowish, limonitic magnetite itabirite. The greenstones, which are commonly weathered, occur in the eastern flanks of the Moeda Syncline, particularly at Mutuca, Tamanduá and Gama mines, and in parts of the Serra da Moeda, such as nearby Retiro das Pedras, Casa de Pedra, and Pau Branco mine.

Some of the lithologies have been found only in Minas Gerais Reunidas (MBR) drill cores at Mutuca mine.

In the upper half of the formation, the greenstone-rich unit, the author (Pires, 1979) has identified a very persistent, 50 to 150 m thick mark horizon, consisting of greenschists, laminated and sheared feldspathic mafic rocks and massive greenstones. The latter consists of fine-grained, massive greenish chloritic matrix with a dust of altered Fe-oxides, with partly weathered tremolitic material; this rock weathers to creamy phyllite and yellowish saprolite. Similar greenstones have been encountered in MBR-drill cores in the eastern part of Tamanduá ore deposit. Metabasitic, amphibolite and chlorite schist lenses occur at the top of the unit and persists

		Bad	Nature of exposures	Drill core records
	CAUÊ ITABIRITE			
	Greenschist with amphibolite lenses			
	Chert lenses			
	Greenschist altered to a creamy phyllite			
	Talc chlorite schist with serpentinite lenticular bodies			
GREENSTONE RICH UNIT	Feldspathic mafic rock			
	Fine-grained mafic rock with micro-breccia and kaolinitic laminae			
	Yellowish magnetite itabirite			
	Massive mafic rock with micro-breccia			
	Feldspathic mafic rock			
	Greenschist (magnetite chlorite schist) with dolomitic lenses			
POTASSIC ALUMINOUS SCHIST UNIT	Tourmalinite layers and lenses			
	Dark gray sericite schist with tourmaline and local finely disseminated graphite			
	Thin lenses of quartzite Breccia zones			
	MOEDA FORMATION Quartz schist			

Figure 2 — Possible stratigraphy of Batatal Formation in the study area: 1 — nature of exposures; 2 — drill core records

upwards within the Cauê Itabirite, as previously found by Dorr and Barbosa (1963) in the Itabira District. Maxwell (1972) described lenticular beds of greenstone, chlorite and talc schist throughout the section of itabirites of the Itabira Group, more common in the lower section, at Catas Altas, Capanema, and Santa Rita Durão quadrangles and considered that the greenstones may represent sills associated with mafic dikes. Thin chert lenses occur seldom. The contacts between the itabirites and the amphibolites are usually marked by 1 to 2 m-thick supergene zones of concretions, composed of hard avocado-like rounded lumps in a limonitic, yellowish cream finegrained matrix; some water springs are developed along this avocado zone, as observed at Pau Branco mine.

Massive to slightly foliated, thick serpentinite lenses interlayered with greenish talc chlorite schist occur in the middle part of the upper section, exhibited in the Tamanduá drill cores (Fig. 3). Underlying this unit there are 50 cm-thick layers of chloritic ultramafic rock alternating with concordant, well-laminated and partly weathered feldspathic mafic rock. This horizon proved to be very persistent, and continuous from the Mutuca, Zoroastro and Tamanduá mines. The rock itself consists of alternating 1 cm-thick whitish bands of kaolinitic and reddish brown mafic material interbedded in a yellowish ferruginous creamy phyllite. A heavy residuum of magnetite, hematite, black tourmaline, apatite, zircon, and elongate limonite pseudomorphs after pyrite was recovered from the weathered kaolinitic banded material by panning. Magnetites recovered from this rock revealed anomalously high amounts of Cr, Ni, V, Ti, and Co.

The above succession grades to a fine-grained foliated to massive chloritic mafic rock with intraformation micro-breccia and kaolinitic lamina with lenses of laminated, yellowish magnetite itabirite. A strongly sheared greenish mafic rock with kaolinitized feldspars forming tiny, flattened lenticles underlies the massive mafic rock containing the intraformation microbreccia described above.

Figure 3 — Section 9400 through the Tamandua Mine (MBR) showing the Batatal Formation with greenstones (GS), serpentinite (S), and sericite schist (SX) units, underlying the Cauê Itabirite Formation with Siliceous Iron Formation (CIF) and Ochreous, Magnetite itabirite (YIF); h — hematite-rich zone; v — sheared amphibolite; s — cherty bands; DDH — diamond drill hole

A thick greenschist succession with sporadic and thin bedded dolomite lenses lie in the lower part of the Greenstone-rich unit. In this succession well foliated talc chlorite schists interfingers with greenschist and sericite schist in the outcrops along the western hills of Serra da Mutuca, near to Highway BR-040. More ubiquitous greenschist occur in the valley between Serras do Curral and Gaivotas, on the left margin of Córrego da Catarina and the western flank of the Serra da Mutuca. The greenschists weathers to a creamy and yellowish clay displaying a preserved foliation with brown stains of Fe-oxides. Probably the persistent exposures of laminated creamy phyllite cropping out in the western flank of Serra da Moeda, underlying Cauê Itabirite is also a weathered greenschist.

The kaolinitic clay deposits described by Pomerene (1964) in the northern part of Tamandua ore deposit were apparently derived from the alteration of the plagioclase-rich amphibolites. The occurrence of several small outcrops of weathered amphibolite still showing a preserved schistose texture with weathered and oriented feldspars, near to the white clay deposits, confirm the above hypothesis.

The feldspathic sheared mafic rock (11/76A and 11/76B in Table 1) may constitute a partly weathered high-alumina basalt as suggested by its low SiO_2 and high Al_2O_3 contents, whereas the quartz muscovite chlorite schist (L-55), found near the base of the greenstone unit, may represent a sub-potassic tholeiitic dacite or perhaps a dacitic tuff as shown by its texture. The talc-chlorite schists (165 and 422) from the middle part of the sequence are characterized by high MgO and relatively low SiO_2 contents. In the sample 165, some of silica occurs as scant, flattened vesicles, where the low Al_2O_3 content is related to the chlorite.

DISCUSSION Despite the confirmed occurrence of greenstones at the upper part of the Batatal Formation in the Moeda Syncline the correlation between these units and those

described by Harder and Chamberlin (1915) at Santa Bárbara is difficult to accomplish. The actual stratigraphic position of the greenstones at Santa Bárbara and Catas Altas has not been clearly explained yet, despite its composition (Sichel, 1982) and textures (spinifex and devitrification) being similar to Archean komatiites, inasmuch as proterozoic and mesozoic komatiites (Etcheverria, 1980) have been found. In fact, the existence of layers of Moeda quartzite and Cauê Itabirite mapped by Maxwell (1972) between the basement migmatitic gneisses and the "Greenstone Sequence" precludes an unquestionable conclusion. These greenstones were considered by Simmons (1968) as mafic intrusives in the Rio das Velhas Series, and by Schorscher (1978, abs.) as the Quebra-Osso Group as forming the basal, ultramafic part of the Rio das Velhas Group, underneath the Nova Lima Group.

Furthermore, the contacts between the units are mostly inferred as pointed out by Maxwell (1972) and by Sichel (1982) who could not establish the real significance of the breccia composed of small angular fragments of serpentinite within a serpentinite-chloritic matrix, located between Nova Lima and Quebra-Osso. The breccia, dualistic interpreted by the latter author, either as erosional or a tectonic breccia or metaultramafic volcanic tuff indicate the inconsistency of the real stratigraphic position of the Quebra-Osso rocks. On the other hand, in the basal parts of the Nova Lima Group (Gair, 1962) or in its correlative Barbacena Group (Ebert, 1957; Pires, 1977) no such rocks were described. As a matter of fact, is equally difficult to correlate the "Greenstone Sequence" or the Quebra-Osso rocks with the greenstones situated on the topmost unit of the Batatal Formation. In addition, at the basal part of Itabira Group, near the center of the Catas Altas quadrangle (Maxwell, 1972), "thin fingers of chlorite schist, interpreted as greenstones, extend into the iron-formation and thin beds of iron-formation into the chlorite schist. The same features were observed between the greenstone and the Batatal Formation, to the north".

Accordingly, the present worker suggests a more detailed study of the stratigraphic position of the Quebra-Osso rocks to be considered or not as the real, basal component of the Archean Rio das Velhas Supergroup rather than a Proterozoic unit. Ultimately the proposed litho-stratigraphic upper section of the Batatal Formation must be confronted and confirmed in other parts of the Quadrilátero Ferrífero, mainly through drill cores, due to the poorly exposed units.

GANDARELA GREENSTONES Guimarães (1931 and 1951) described amphibole schists, chlorite schists or prasinites, and talc schists together with itabirites, dolomitic, and tremolitic itabirites within the rock sequence found at Caeté and Nova Lima in the Quadrilátero Ferrífero, later shown (Dorr *et al.*, 1957) to pertain to the Archean Rio das Velhas Series; however that author reported also on the existence of mafic schists within the typical Minas rocks at Serras do Curral and Moeda and Fecho do Funil (Rio Paraopeba, near Brumadinho). The author suggested that the mafic schists, derived through the metamorphism of basaltic flows and tuffs resulted from submarine volcanism, would constitute, together with the itabirites, the middle unit of the Minas Series. Few descriptions of a Gandarela greenschist of possible volcanic origin have been made by Johnson (1962) from north of Ribeirão da Colônia (Dom Bosco quadrangle) who observed small oval shaped bodies flattened parallel to schistosity filled up by quartz and chlorite which could be interpreted as amygdulites. Guild (1957) described a "gray to purplish gray fine-grained rock containing abundant rounded

bluish quartz grains, with oriented flattened limonite blebs and microscopic oriented sericite flakes and cryptocrystalline quartz (?) plus minor plagioclase and microcline, interpreted as a tuff or an acid flow or sill rock with possible remnants of a welded crystal tuff at Esmeril (Congonhas) within the Minas Series".

The Sítio Largo Amphibolite ascribed to the Gandarela Formation, in the Monlevade quadrangle by Reeves (1966) could be correlated with the partly weathered amphibolite found in the upper section of the Gandarela Greenstone sequence at Morro do Chapéu road. It appears then, that mafic and possible felsic volcanic rocks were widespread, and represent a period of volcanism after the deposition of the itabirites. The extent of these rocks may be even greater should the Sítio Largo Amphibolite, above the Cauê Itabirite, also be of volcanic origin. Simmons (1968) described mafic dykes and sills transformed into chlorite schist at the upper part of the Gandarela Formation in the Barão de Cocais area. Dorr (1969) considered the dolomites, dolomitic phyllites and minor iron formation as the main lithologies of the Gandarela Formation.

Nonetheless this author found that the schistose greenstones of the Gandarela Formation, which overlie the Cauê Itabirite almost everywhere in Quadrilátero Ferrífero, constitute the main lithology of the unit, in terms of thickness and abundance. The main rock consists of magnetitic chlorite schist apparently derived from a reworked ultramafic volcanic rock (P-22 in the Table 1). The Gandarela greenstones form two wide belts in the Moeda Syncline meeting in the nose of structure at its junction with the Curral Anticline and near Serra do Saboeiro where is tightly folded together with Cercadinho Formation (Fig. 4). Good outcrops of the greenstone can be studied between km 396 and 440, and km 410 of the Highway BR-040, and along the Córregos do Carango, Eixo and Lopes, in the Ribeirões do Silva and Mata Porcos, and in poor roadcuts of the Morro do Chapéu road. In the Ribeirões do Mango and Colônia (Dom Bosco quadrangle) good exposures of fresh greenstone occur, at Buraco do Engenho Grande and Bocaina quarries, the greenstone encompasses lenses of stromatolitic dolomite and in the Capitão do Mato potent dolomite lenses are enclosed within the schistose ultramafic rock. There are good outcrops in roadcuts along the Morro do Chapéu road, and in the Feixos-Ouro Podre water supply area.

In general, the greenstone is well foliated and chloritic. In this chloritic matrix are perfect magnetite octahedra, or clusters of magnetite grains, from submicroscopic to about 1/4 mm in diameter. Some of the magnetite is random in occurrence, and some form 1/2 to 2 mm, magnetite-rich laminae in a generally chloritic matrix. Locally, as for example at km 394 and 396 (BR-040) magnetite octahedras partly transformed into hematite, occur in 2 to 5 mm grains associated with rutile.

In the creek between Córrego do Eixo and Córrego do Lopes there are whitish layers several millimeters thick, in the greenschist, formed of quartz and kaolinite after feldspar. There are also very thin, bright green, talc-rich layers in the greenstone.

The greenschist weathers to a varicolored clayey saprolite with preserved schistosity. In partly weathered material the common colors are white, red, brown, purple, yellow and greyish. Westward of the greenstone exposure on the Morro do Chapéu road there is an outcrop of weathered, yellowish-brown microbrecciated amphibolite. Angular breccia fragments, less than 15 mm in size are distributed irregularly within the matrix. Within a few meters, the material loses its

Figure 4 — Cross section through Serras do Saboeiro and Moeda

brecciated character, increases in feldspar content, and grades into a rock with a porphyritic texture to form an amphibolite. This amphibolite, which crops in an extension of at least 400 m along the Morro do Chapéu road is slightly banded. This banding is emphasized by the preferred orientation of feldspars, which range in size from 1 to 5 mm, are now kaolinite, and mafic minerals are hydrated and altered. This rock crops out also in the hill behind the Skol Brewery.

At the northern flank of the Dom Bosco Syncline, near Alto do Monumento, another interesting section (Fig. 5) displays a basal 80 m-thick schistose to massive greenstone (2), overlying the Cauê Itabirite (1); magnetite-rich laminae are concentrated downward and Mn-oxide bands upward. Overlying this unit there is a 6 m-thick, dark grey cherty quartzite (3) forming 30 to 35 cm-thick bands interlayered with thin, 1 to 2 cm-thick bands of silvery sheen phyllite. A 30 m-thick, well-laminated greenstone (4), which succeeds the quartzite, consist, downward of a zone composed by scant 3 cm-thick Mn-oxide bands and upward the Mn-oxide bands intermingle with minor kaolinitic lamina (5). Another 2 cm-thick whitish grey, cherty quartzite layer (6) occurs on top of the Mn-rich greenstone. A 35 m-thick mixed schistose greenstone sequence (7) begins, at the base with magnetite-hematite-rich seams and abundant Mn-oxide bands rare black graphitic lamina predominates in the lower to middle sections. Flattened kaolinitic lamina and lenticles with non-oriented tiny and slender topaz microprisms are distributed in the middle and upper sections. The latter unit grades to a 15 m-thick, strongly laminated rock (8) with abundant kaolinitic lamina alternating with sericitic and chloritic lamina and bands. A 8 m-thick, partly weathered reddish massive greenstone (9), overlies the kaolinite rich zone and in underneath a 0.5 m-thick, brownish black wad layer (BT). A 30 m-thick, medium grained sericite-muscovite schist (Sx) with distinct well-developed muscovite blades and minute magnetite octahedra apparently, forms the upper unit together with a ubiquitous and persistent 2 m-thick wad horizon (BT). A conformable quartz-muscovite-kaolinite-specular-hematite-topaz-(pyrite) vein restricted to the BT-horizon occurs along the contact zone among the muscovite schist (Gandarela) and the quartzite-silver phyllite of the Cercadinho Formation. The position of the topaz-bearing vein contrasts with Olsen's opinion (1971) that the topaz deposits lie within the Sabará Formation.

Dolomites have been found as lenses within the lower section of the Gandarela Formation by this author, some of them displaying stromatolite columns and sheeflike algal colonies enclosed within greenstone. Stromatolites associated with mafic volcanic rocks of the Wolkberg Group of South Africa have been described by Button (1972), who suggested that

Table 1 — Chemical composition of greenstones of the Batatal and Gandarela formations

	11/76A	11/76B	L-55	165	422	P-22	SL	330	LH	Rod	TB
SiO ₂	42,06	45,26	67,68	53,62	48,10	35,10	48,4	43,16	50,3	35,69	50,83
TiO ₂	0,27	1,10	0,69	0,17	0,22	2,70	1,4	1,29	—	0,07	2,03
Al ₂ O ₃	26,72	27,38	12,60	2,91	8,80	10,30	15,7	28,31	16,6	2,77	14,07
Fe ₂ O ₃	19,45	16,87	10,04	9,14	12,08	29,80	3,3	16,41	3,7	10,52	2,88
FeO							9,9	—	8,9	0,80	9,00
MnO	0,51	0,17	0,15	0,21	0,03	0,09	0,2	0,44	—	0,12	0,18
MgO	4,03	3,12	2,87	26,68	26,66	19,10	6,1	2,32	6,9	34,39	6,34
CaO	4,01	1,10	0,05	0,30	0,05	0,37	9,5	0,11	10,0	2,45	10,42
Na ₂ O	0,94	1,50	0,23	0,04	0,24	0,19	1,7	0,48	2,9	0,06	2,23
K ₂ O	0,42	0,63	1,46	0,12	0,11	0,10	0,34	3,98	0,7	0,05	0,82
H ₂ O	—	—	3,35	6,02	3,68	2,30	2,6	3,43	—	10,49	0,91
P ₂ O ₅	0,13	0,13	0,05	0,08	—	—	0,13	—	—	0,02	0,23
Total	98,54	97,26	99,48	99,21	99,97	100,05	100,44	99,99	100,0	99,43	99,94

Explanations to Table 1: 11-76A — Metabasite DDH 11/76, depth 60-67 m — Tamanduá Mine. 11-76B — Metabasite DDH 11/76, depth 67-78 m — Tamanduá Mine. L-55 — Metabasite (chlorite magnetite schist) — Retiro das Pedras Club. 165 — Metabasite (Talc chlorite schist with chert laminae) (km 440 Highway BR-040). 422 — Metabasite — Talc chlorite schist (Western part of Mutuca mine). P-22 — Metabasite — Schistose greenstones (magnetite talc-chlorite schist, km 439 Highway BR-040). SL — Sítio Largo Amphibolite. Gandarela Formation (Reeves, 1966). 330 — Metabasite (chloritoid schist formation), near Dom Bosco. LH — Lapadu-Hargues, average of amphibolites (Lapadu-Hargues, 1953). Rod — Serpentinized ultramafic rock (Roodekrans Complex, Anhaeusser, 1976). TB — Average tholeiitic basalt (Nockolds, 1954, 137 analysis). Metabasite indicated done by this author at MTU 303 Perkin Elmer AAS

Figure 5 — Cross section through the Gandarela Formation at Alto do Monumento. Dom Bosco quadrangle: m — magnetite-rich lamina; Mn — Mn-oxide-rich bands; k — kaolinitic lamina; g — graphite lamina; BT — wad; SX — sericite schist. See text for numbers and other symbols

the algal colonies evolved prior to about 2.0 billion years ago in small volcanic lakes, different to the shelf-carbonate deposition. The Gandarela stromatolites present a similar depositional setting, that is, they form restricted lenticular bodies within mafic volcanic rocks, suggesting similar environment to that found in recent barrier reef formations. A spectacular dolomite lens occurs in a roadcut near km 81 of the Highway BR-356, enclosed within an ultramafic greenstone of the Gandarela Formation. Apparently all these dolomite lenses occurring near the base of the unit are iron-rich, revealed by its higher magnetite or hematite content.

In the schistose greenstone, deep green to greyish chlorite forms the foliation and constitutes 80 percent of the rock. Octahedral magnetite porphyroclasts, scattered throughout the matrix or forming distinct magnetite bands, constitute about 8 percent of the rock. Rutile occurs as rounded and elongated grains within magnetite as well as in grain clusters

and in composite grains within magnetite. Talc and stilpnomelane occur in pressure shadow fringes, in large flakes, around magnetite, and are also associated with matrix chlorite. Feldspar, apatite and sphene occur in lesser amounts.

The main type of the Gandarela greenstone has a relatively high abundance of MgO, FeO and Al₂O₃, and low abundance of alkalis and CaO, giving rise to the formation of Mg-chlorites (Table 1). Such chlorite are stable under low to high grades of metamorphism. These Mg-rich rocks are interpreted to represent serpentinized komatiitic rocks, metamorphosed under high PH₂O and strong dynamic conditions. In a two-step process the pre-existing peridotite is thought to have been serpentinized and then converted to a silica-deficient talc-chlorite-magnetite assemblage. A higher fCO₂ during serpentinization favor outward migration of CaO from the ultramafic. The existence of Al₂O₃ implies the formation of chlorite, but its original form is still questionable. Magnetite remained as one of the initial products of serpentinization by the olivine breakdown and behaved as rigid porphyroclasts during chloritization, which could be synchronous to the deformation.

In the ACF-diagram (Fig. 6) the Gandarela greenstone (P-22) together with other greenstones (G-1, 422 and 165) fall within the chlorite-talc-epidote field of low-grade metamorphism, very close to the composition of the ideal chlorite (large bar), and close to the talc corner, strongly suggesting an ultramafic affiliation.

GEOCHEMISTRY Twenty samples of magnetite (Fig. 1 and Table 2), carefully separated from Gandarela greenstones, and one of itabirite, have been analysed for Cr, Ni, V, Ti, and Co by using the 360 Perkin Elmer AAS (Pires, 1976). The samples are grouped in four clusters according to the real distribution and showed higher concentrations of Ni, Cr, and Ti in the areas n. 1 and 3, V and Co in the area 2 and general low values in the area 4.

Some samples, as P-22, 14R, and 29E contain exsolved rutile (Fig. 7, C and D) insoluble in hot HCl consequently not detectable in the analysis. On the other hand, the samples 2-B and 31 (area 3) revealed abundant rounded Ti-rich

Table 2 — Cr, V, Ti, Ni, and Co content in magnetites (ppm)* (see map for sample locations)

Samples	Ni	V	Cr	Co	Ti
Area 1					
PT-1	104	170	96	31	3,300
103	2,000	196	503	75	7,600
36	68	70	494	21	3,290
62	117	125	445	27	2,583
107	90	218	521	29	5,500
29A	387	225	120	22	4,360
29B	65	195	150	20	5,700
Area 2					
69	135	484	101	130	875
P-22	75	366	35	55	458
A-A	190	297	246	38	290
Mag1	144	523	42	150	500
14R	608	506	41	65	533
48	408	203	386	150	1,333
Area 3					
2-B	339	190	217	160	6,500
29E	63	425	524	22	4,675
X	468	297	418	100	4,635
79E	105	289	240	53	2,040
31	920	234	265	2,500	5,850
Area 4					
2	83	103	33	19	900
BT-1	56	125	23	16	283
79	58	133	23	16	956
Averages	309	256	234	60	3,094

* Done by the author in the MTU 360AAS

Figure 6 — Low-grade ACF-diagram of rocks of the Gandarela (P-22, 330 and SL) and Batatal Formations (11-76-A/B, L-55, 165 and 422); G-I, G-II and G-III — Nova Lima greenstones; TB — average tholeiitic basalt (Nockolds, 1954); LH — average of amphibolite (Lapadu-Hargues, 1953); Ch — chlorite; Ac — actinolite; Zo — zoisite. Mean value of tholeiites indicated (large square)

blebs within the magnetite (Fig. 7, A and B); this type of inclusions may represent an emulsion texture, apparently formed upon cooling of magnetite by expelling the excess of Ti (grey blebs) along with silicate-rich glass or pleonaste. However the irregular shapes of the magnetite grains and the absence of ilmenite laths preclude a conclusion about the formation temperatures. Some of the spinel-rich undigested blebs have been already described (Haggerty, 1976) within oxidized basalts. Broad beam and quantitative electron microprobe analysis confirmed the higher Ti-values found. Coincidentally the second higher Ni-value (920 ppm) has found in the same sample, as well as Co (2,500 ppm) thus corroborating an ultramafic affiliation. On the other hand, rutile grains may develop over the trellis-lamellae of hematite laths within magnetite, formed upon the oxidation process.

The study of the geochemistry of transition elements in Fe-Ti oxides, particularly Cr, Ni, V, and Co, is important because they are concentrated in mafic solid phases and consequently are depleted in residual liquids, thus generally decreasing with differentiation. The ranges of concentrations of the concerned elements in the mafic and ultramafic rocks are two or three orders of magnitude higher than the intermediate and felsic rocks. The behaviour of Cr and Ni in the ultramafic is quite similar, both sharply decreasing along differentiation, but while Ni concentrates predominantly within olivines, Cr could either form chromite or accumulates within magnetite, olivine or plagioclase. Usually Ni and Cr content in these magnetites range among 60 and 1,500 ppm for Ni, between 40 and 2,500 ppm for Cr. Compared with coexisting olivines, pyroxenes show higher Cr and V, and lower Ni and Co contents. With fractionation augites show depletion in Cr, V and Ni, in general.

Seemingly Co shows a greater affinity for sulfides than does Ni, thus being more sulfophile and also for the Mn-oxide minerals. Accordingly the Co contents in the exam magnetite is low.

CONCLUSIONS Schistose greenstones represented by talc chlorite schists, talc chlorite magnetite schists, chlorite schists, and metabasites have been identified within topmost part of the Batatal Formation and the lowermost part of the Gandarela Formation. The SiO₂-contents, in general ranging from 35 to 53 percent and high MgO-values broadly support contents in magnetites separated from the greenstones also reflect Ni, Ti, Cr, and V values comparable to those found in ultramafic or mafic rocks.

The Ti-rich glass inclusion and blebs found in some magnetite may corroborate the proposed origin. The relative position of the studied greenstones encompassing the main itabiritic iron formation may indicate a volcanogenic facies with a rather different source for the iron, postulated in previous works.

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Figure 7 — Magnetites from the Gandarela Formation: A — magnetite grains displaying exsolved Ti-rich and silicate blebs. Hematite lamellae along (111) planes also shown (sample 31); B — slightly oriented Ti-rich blebs within magnetites (sample 31); C — rutile (R) at the edge of magnetite octahedra with hematite lamellae (sample 14-R); D — disoriented rutile transecting hematite lamellae within a magnetite grain (sample P-22). Bar is 0.03 mm

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