Geochimica Brasiliensis, 21(1)009 - 021, 2007

Geochimica Brasiliensis

THE GENESIS OF THE METAULTRAMAFITES FROM CLÁUDIO (MG)

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Recebido em Abril de 2006, aprovado para publicação em novembro de 2006

ABSTRACT

The metaultramafites from Cláudio (Minas Gerais, Brazil) are constituted by orthopyroxene, forsterite, Cr-spinel, amphiboles, Mg-chlorite, serpentine, talc, oxides and sulphides. The magmatic paragenesis underwent high-grade metamorphism, causing recrystallization of their mineral constituents. After, with the hydration of this paragenesis and the drop of temperature, part of the pyroxene and olivine was replaced by amphiboles, talc and Mg-chlorite. The metaultramafites contain minerals and textures indicate a magmatic crystallization of the cumulus-type in a plutonic to sub volcanic environment. However, quartzite and iron formation associated with metaultramafites suggest a volcanic to sub volcanic origin in greenstone belt-type environments. It is likely that this sequence is correlated with the Rio das Velhas Supergroup.

RESUMO

Os metaultramafitos de Cláudio (Minas Gerais, Brasil) são constituídos por ortopiroxênio, forsterita, Cr-espinélio, anfibólios, Mg-clorita, serpentina, talco, óxidos e sulfetos. A paragênese magmática foi submetida a metamorfismo de alto grau, causando a recristalização seus minerais. Em seguida, com a hidratação dessa paragênese e a queda da temperatura, parte do piroxênio e da olivina foi substituída por anfibólios, talco e Mg-clorita. Os metaultramafitos contêm minerais e texturas que indicam uma cristalização magmática do tipo cumulus em um ambiente plutônico a subvulcânico. Porém, quartzitos e formação ferrífera associadas aos metaultramafitos apontam para uma origem vulcânica a subvulcânica em ambientes do tipo greenstone belt. É provável que essa seqüência seja correlacionável ao Supergrupo Rio das Velhas.

INTRODUCTION

In this contribution, the results of a geologic study focusing the metaultramafic rocks that crop put in the Serra do Barão (Barão Ridge), city of Cláudio (MG), are presented. Geologically, this region is inserted in the tectonic context of the southern portion of the São Francisco Craton (Figure 1).

This cratonic fragment is constituted predominantly by a Neoarchean sialic substrate composed of high-grade metamorphic terranes (high amphibolite – granulite facies), which underwent retrograde metamorphism at various degrees, and subordinately by supracrustal sequences and varied intrusives (Carneiro et al. 1998a, 1998b; Fernandes & Carneiro 2000; Oliveira & Carneiro 1999; Teixeira et al. 2000). Among the intrusives, NW/SE-striking gabbronorite and gabbro dikes stand out in the Serra do Barão (which trends NE/SW, Figure 1), intruding both the sialic substrate (gneissic rocks) and the supracrustal sequence. These dikes are approximately parallel and can reach up to 200 m in width. The Serra do Barão supracrustal sequence is formed by amphibolite, metaultramafite, quartzite, banded iron formation and schist (Figure 1). The amphibolite crops out only locally as small, strongly weathered blocks associated with an ochre clayey soil. Quartzite lenses and the banded iron formation intercalate the metaultramafic rocks and form the highest crests of the Serra do Barão. Scarce occurrences of schistose rocks intercalate the metaultramafites and the quartzite. The outcrops of the metaultramafic rock types are concentrated in topographic lows and form blocks reaching up to 7m in size. As the other rock types of the region, these rocks are strongly weathered, producing clay-rich, dark red to brown soils. Despite the metamorphic and deformational processes that affected the ultramafic rocks after magmatic crystallization, they still exhibit relict

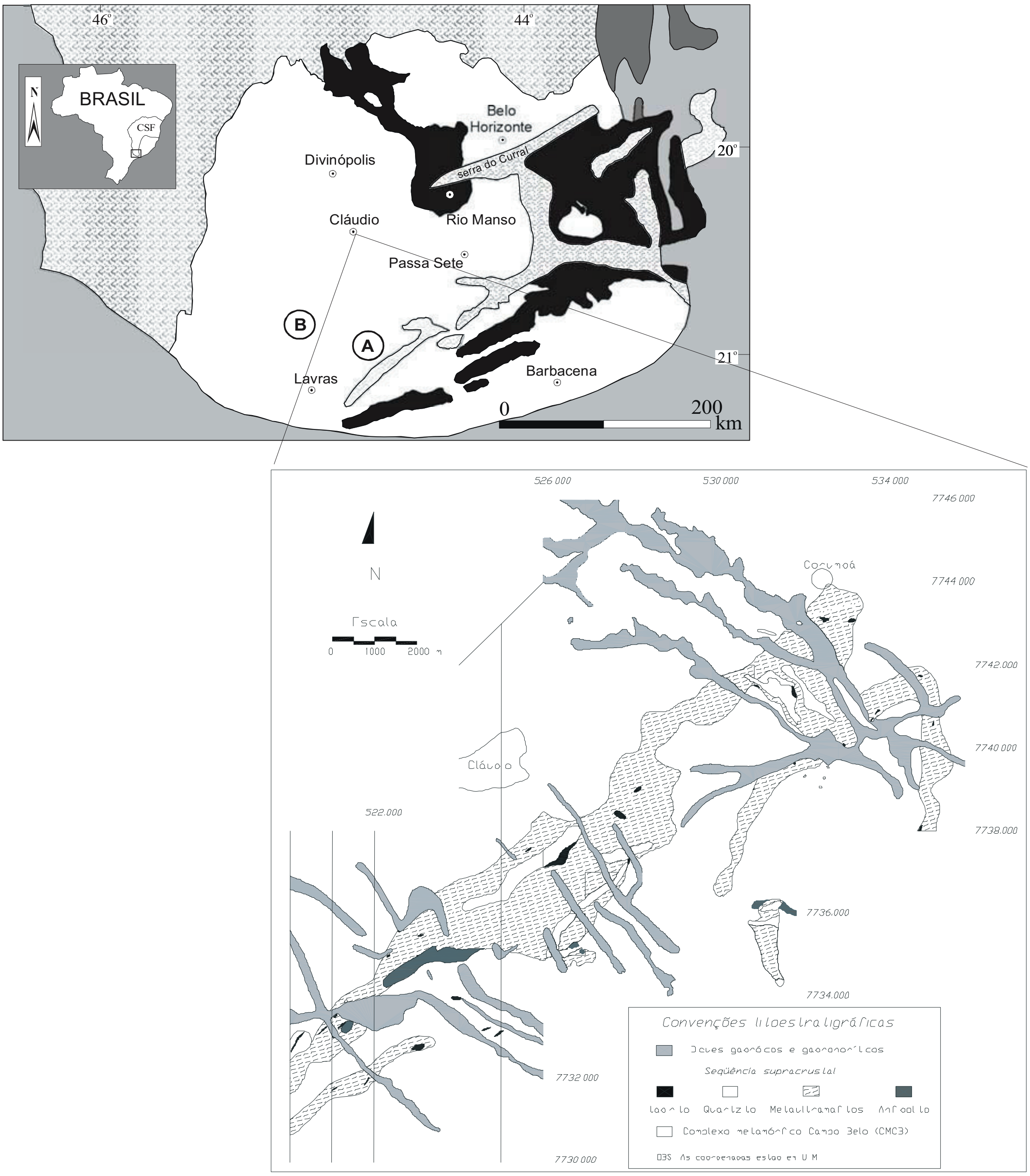

Figure 1: Localization and geological map of the study area.

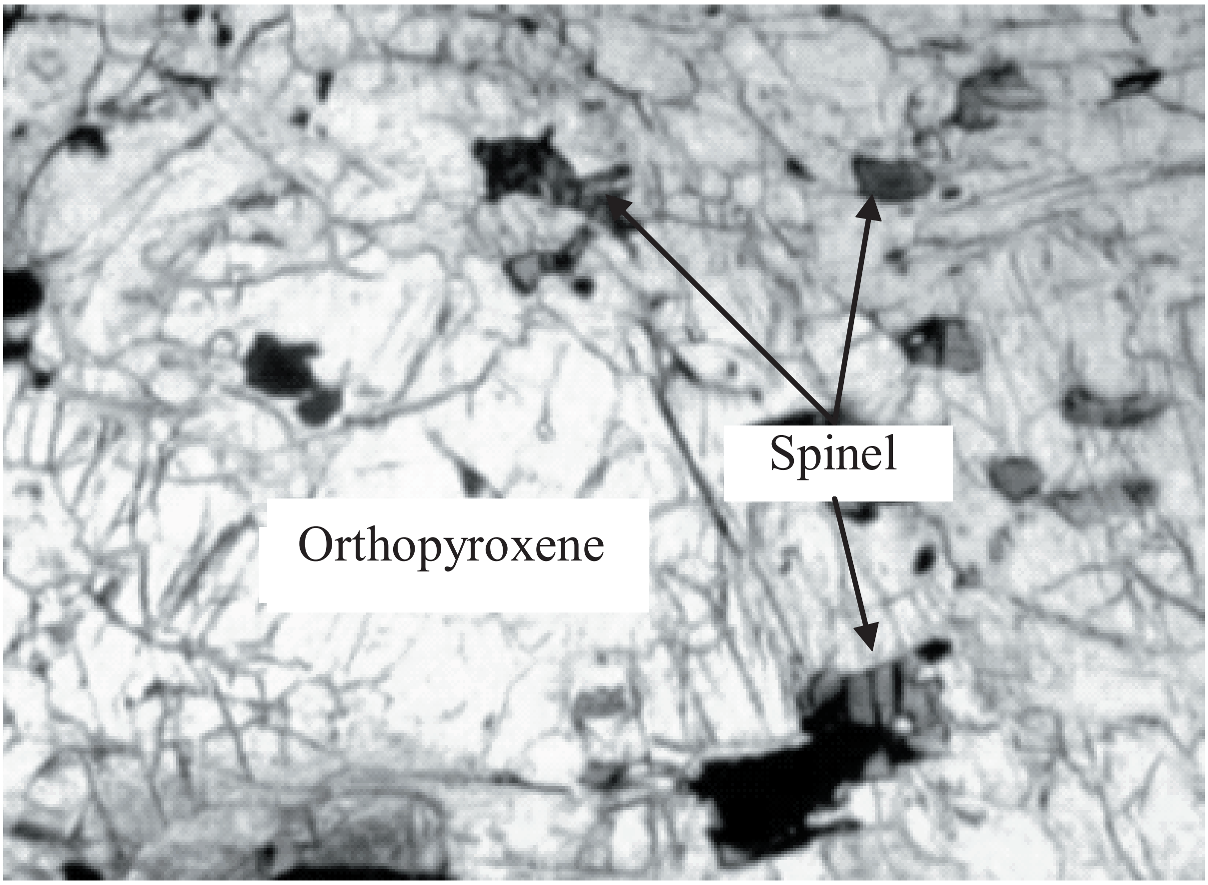

Figure 2: Ultramafic rocks with relict cumulatic textures, characterized by olivine and orthopyroxene crystals rimmed by clinoamphiboles.

cumulatic textures (Figure 2), characterized by olivine and orthopyroxene crystals rimmed by clinoamphiboles (magnesian hornblende and actinolite) and spinel included into ortopyroxene crystal (Figure 3).

This fine to coarse grained mineral assemblage is arranged in alternating (strongly serpentinised) olivine-rich and coarse-grained orthopyroxene-rich levels. Olivine occurs as rounded grains with rims composed of clinoamphiboles. It alters to anthophyllite, serpentine or Mg-chlorite. Subordinately, Cr-spinel inclusions occur in olivine. Orthopyroxene is usually granular, medium to coarse grained and shows some evidence of alteration to anthophyllite and Mg-chlorite. Cr-spinel inclusions are more abundant in the orthopyroxene. The clinoamphiboles (magnesian hornblende, tremolite and actinolite) are granular or prismatic, fine to medium-grained, and together with anthophyllite, form seriate and/or decussate textures in the metaultramafites. Anthophyllite is less abundant, acicular, and fine to medium-grained. It overgrows orthopyroxene and olivine and truncates the other amphiboles, therefore being a later phase. Biotite (up to 5%) is present in some samples. Sulfides and oxides are fine to medium-grained, euhedral to sub-euhedral. Cr-spinel shows a zoning defined by olive-green rims and dark-green to brownish centers (Figure 4).

Finally, the presence of serpentine and Mg-chlorite variably substituting orthopyroxene and olivine crystals is common. Petrographically, the metaultramafites can be classified as metaperidotite and olivine- and spinel-bearing metapyroxenite.

METHODS

In addition to the geologic mapping (1:10,000 scale) and petrography, chemical mineral analyses were carried out by electronic microprobe. Ten samples from Cláudio metaultramafites were analyzed in the Microanalysis Laboratory (LMA) of the Departament of Physics of the Institute de

Ciências Exatas of Universidade Federal de Minas Gerais. Polished thin sections were coated with graphite in order to increase electrical conductivity. The equipment used was a JEOL JXA-890ORL microprobe and the operating conditions were: 20hA current and 40-second counting time, 15kV for silicates and 20kV for sulfides and oxides.

MINERAL CHEMISTRY

The following phases were chosen from several mineral assemblages to be analyzed by the electronic microprobe: orthopyroxene, olivine, spinel, amphiboles, chlorite and serpentine. Table 1 shows the average compositions obtained for the minerals analyzed. Orthopyroxene (Table 1 and Figure 5a) presents 78.37% to 86.26% of enstatite (En).

Mg contents are high (En78-86 Wo0.2-0.6 Fs13-21) and Al contents constrained to the 0.93% - 3.14% interval. The Mg number (Mg# = Mg/Mg+Fe^{2+}) varies from 0.83 to 0.93. Orthopyroxene is depleted in the following oxides: CaO (average = 0.17%) and Na2O (average = 0.01%). Three varieties of clinoamphiboles (magnesian hornblende, tremolite and actinolite) were identified, all of them Ca-enriched (Table 1 and Figures 5c and 5d). Clinoamphiboles is more abundant than orthoamphiboles (anthophyllite). Magnesian

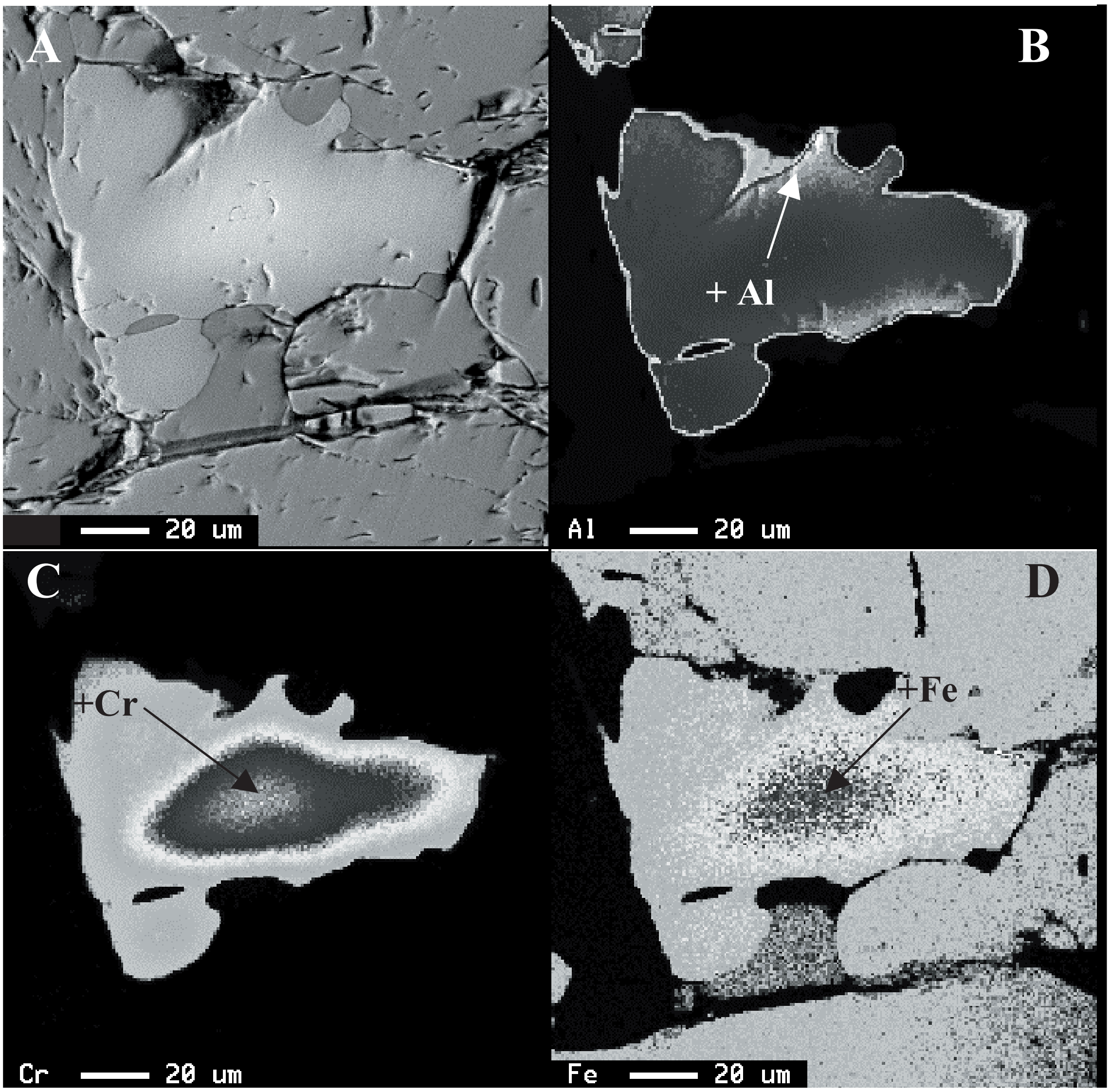

Figure 4: Compositional mapping of a spinel crystal from a Cláudio metaultramafite, using the WDS and EDS microanalysis techniques. A - Image of Backscattered electrons; B - Image showing Al contents in the crystal; C - Image showing Cr contents in the crystal; D - Image showing Fe contents in the crystal.

Table 1: Average composition and standard deviation of the silicate phases of the Cláudio metaultramafic rocks. 1 - Average of 60 points in orthopyroxene; 2 - Average of 11 points in orthoamphiboles; 3 - Average of 69 points in clinoamphiboles; 4 - Average of 5 points in chlorites. Compositional parameters: mg=Mg/(Mg+Fe^{2+}); En=100Mg/(Mg+Fet+Mn+Ca); Wo=100Ca/(Ca+Mn+Fe^t+Mg); Fs=100(Fe^t+Mn)/(Fet+Mn+Mg+Ca).

	Orthopyroxene			Orthoamphibole			Clinoamphibole			Chlorite	
	A.C. (%)	S.D.		A.C. (%)	S.D.		A.C. (%)	S.D.		A.C. (%)	S.D.
SiO_2	54.73	0.87	SiO_2	55.91	2.11	SiO_2	52.63	1.76	SiO_2	28.29	0.43
TiO_2	0.06	0.02	TiO_2	0.07	0.04	TiO_2	0.34	0.14	TiO_2	0.13	0.08
Al_2O_3	1.76	0.55	Al_2O_3	1.75	0.51	Al_2O_3	6.81	2.03	Al_2O_3	23.17	0.25
FeO*	8.01	1.60	FeO	11.31	1.76	FeO	4.71	1.17	FeO	7.46	0.18
Fe_2O_3*	3.10	0.99	Cr_2O_3	0.07	0.04	Cr_2O_3	0.24	0.15	MnO	0.03	0.02
Cr_2O_3	0.09	0.04	MnO	0.26	0.06	MnO	0.10	0.05	Cr_2O_3	0.13	0.07
MnO	0.24	0.07	MgO	28.01	2.00	MgO	20.02	1.10	MgO	28.56	0.22
NiO	0.06	0.06	CaO	0.46	0.13	CaO	12.26	0.95	CaO	0.03	0.06
MgO	31.92	1.14	Na_2O	0.06	0.04	Na_2O	0.54	0.23	Na_2O	0.01	0.00
CaO	0.19	0.06	K_2O	0.01	0.01	K_2O	0.13	0.06	K_2O	0.01	0.01
Na_2O	0.01	0.01	F	0.02	0.04	F	0.03	0.04	F	0.01	0.03
Total	**100.17**	0.51	**Total**	**97.87**	0.99	**Total**	**97.58**	0.73	**Total**	**87.83**	0.69
Si	1.92	0.02	TSi	7.75	0.23	TSi	7.30	0.22	TSi	5.40	0.04
Ti	0.00	0.00	TAl	0.18	0.15	TAl	0.70	0.22	TTi	0.02	0.01
Al	0.07	0.02	TFe^3	0.00	0.00	TFe^3	0.00	0.00	TAl^{IV}	2.60	0.04
Fe^{2+}	0.24	0.05	TTi	0.00	0.01	TTi	0.00	0.00	Soma T	8.00	0.00
Fe^{3+}	0.08	0.03	Soma T	7.94	0.10	Soma T	8.00	0.00	$M1Al^{VI}$	2.61	0.05
Cr	0.00	0.00	M1Al	0.10	0.09	M1Al	0.42	0.15	M1Fet	1.19	0.03
Mn	0.01	0.00	M1Cr	0.01	0.00	M1Cr	0.03	0.02	M1Mn	0.00	0.00
Ni	0.00	0.00	$M1Fe^3$	0.00	0.00	$M1Fe^3$	0.07	0.10	M1Cr	0.02	0.01
Mg	1.67	0.05	M1Ti	0.00	0.00	M1Ti	0.04	0.01	M1Mg	8.12	0.07
Ca	0.01	0.00	M1Mg	4.89	0.09	M1Mg	4.14	0.21	M1Ca	0.01	0.01
Na	0.00	0.00	$M1Fe^2$	0.00	0.00	$M1Fe^2$	0.31	0.10	M1Na	0.00	0.00
Total	4.00	-	Soma M1	5.00	0.00	Soma M1	5.00	0.00	M1K	0.00	0.00

Table1: Continuation

Orthopyroxene			Orthoamphibole			Clinoamphibole			Chlorite		
	A.C. (%)	S.D.		A.C. (%)	S.D.		A.C. (%)	S.D.		A.C. (%)	S.D.
TSi	1.92	0.02	M2Mg	0.91	0.35	M2Mg	0.00	0.02	Soma M1	11.97	0.04
TAl	0.08	0.02	$M2Fe^2$	1.32	0.22	$M2Fe^2$	0.16	0.12	Total cátions	19.97	0.04
Soma T	2.00	-	M2Mn	0.03	0.01	M2Mn	0.01	0.01	Fet/Fet+Mg	0.13	0.00
M1Al	0.00	0.02	M2Ca	0.03	0.04	M2Ca	1.82	0.14	Mg/Mg+Fe	0.87	0.00
M1Ti	0.00	0.00	M2Na	0.01	0.01	M2Na	0.00	0.00	Al^{VI}+Cr/Al^{IV}	1.00	0.03
M1Cr	0.00	0.00	Soma M2	2.29	0.38	Soma M2	2.00	0.00	Al^{IV}-(Al^{VI}+2*Ti+Cr)	-0.06	0.08
$M1Fe^{3+}$	0.08	0.03	M3Ca	0.03	0.04	M3Ca	0.00	0.00	Ca+Na+K	0.01	0.01
M1Mg	0.92	0.02	M3Na	0.01	0	M3Na	0.15	0.06	Al^{IV}	2.60	0.04
M1Ni	0.00	0.00	M3K	0.00	0.002023	M3K	0.02	0.01	Al^{VI}	2.61	0.05
Soma M1	1.00	-	Soma M3	0.05	0	Soma M3	0.17	0.07	Al_{total}	5.21	0.03
M2Mg	0.75	0.05	Total Cátions	15.28	0.345252	Total Cátions	15.17	0.07			
$M2Fe^{2+}$	0.24	0.05	Total Oxigênios	23	0.286287						
M2Mn	0.01	0.00									
M2Ca	0.01	0.00									
M2Na	0.00	0.00									
Soma M2	1.00	-									
Total Cátions	4.00	-									
Mg#	0.88	0.03									
En	83.44	2.27									
Wo	0.35	0.11									
Fs	16.21	2.25									

hornblende is present in a wide range of magmatic rocks and its composition will depend on the magma from which it crystallized (Spear 1981). Therefore, doubts remain whether magnesian hornblende is an igneous phase that recrystallised later or derived, during metamorphic processes, from an igneous pyroxene that composed the intercumulus material. Anthophyllite, however, does not result from magmatic crystallization and commonly appears in metaultramafic bodies (e.g. serpentinised peridotites), under lower amphibolite facies conditions (Deer et al. 1996), forming after olivine and orthopyroxene, with which it is frequently associated. Olivine (Table 2 and Figure 5b) is forsterite (Fo91), with general formula [(Mg 1.58-1.75, Fe 0.3-0.47) 2(SiO_4)] and Mg# between 0.77 and 0.86.

The chlorite (Table 2) is magnesian and can be classified as sheridanite. Its molecular formula is {(Mg8.03-8.2 Fe1.16-1.22 Cr0.01-

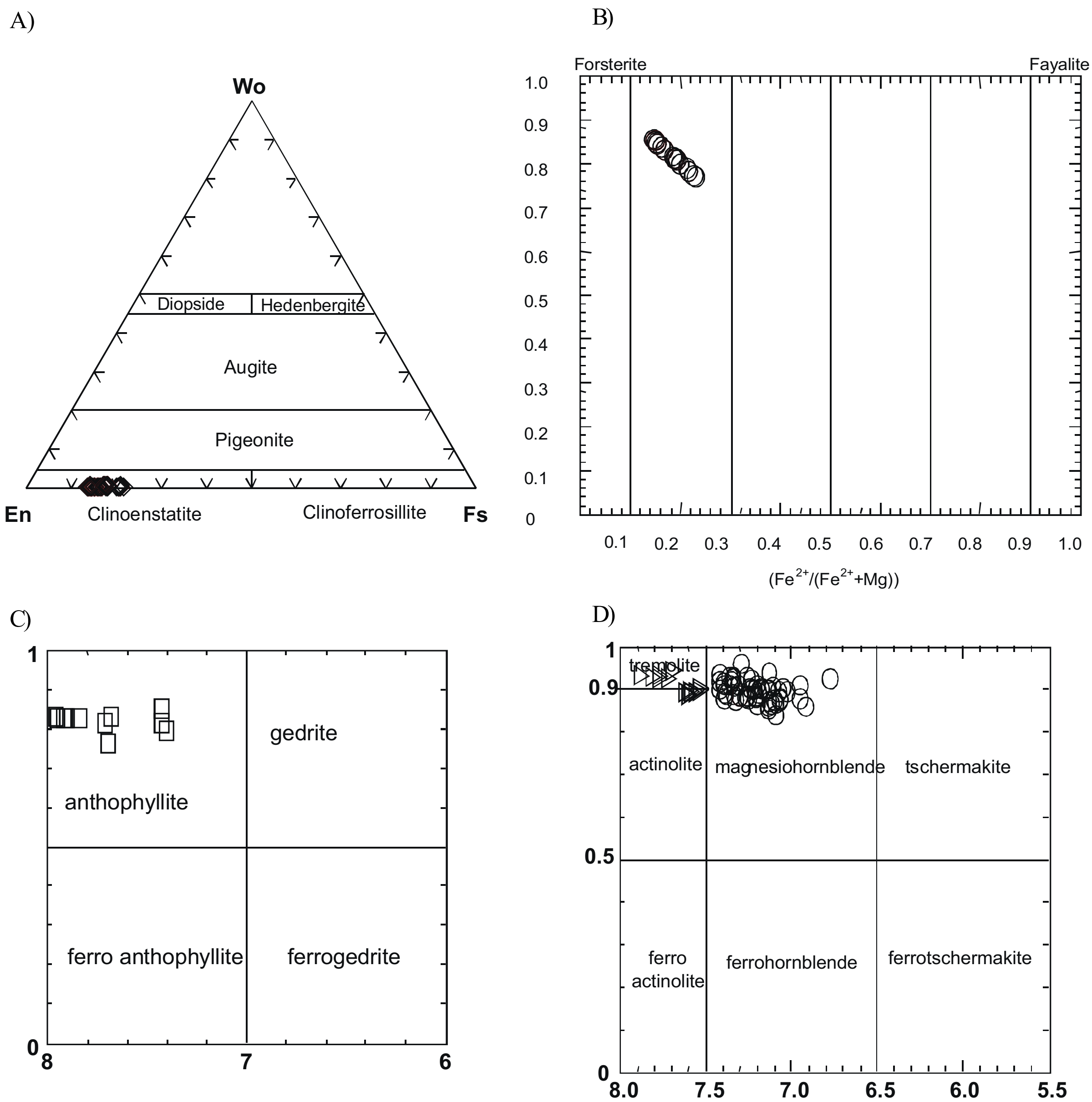

Figure 5: A – Classification of orthopyroxenes, in terms of enstatite and ferrossilite molecules (based on Morimoto 1988); B - Classification of olivines, in terms of forsterite and fayalite molecules; C – Diagram Si *versus* Mg/(Mg+Fe^{2+}) of orthoamphiboles (based on Leake *et al.* 1997); Diagram Si *versus* Mg/(Mg+Fe^{2+}) of clinoamphiboles (based on Leake *et al.* 1997).

0.03 Al2.56-2.67)12[(Si5.34-5.44 Al2.56-2.66)8 O20](OH)16}. Tetrahedral Al varies from 2.56% to 2.66%. The Cláudio spinels (Table 2) are of aluminous composition, with considerable Mg, Fe and Cr contents and can be classified as Cr-spinel or hercinite (Deer et al. 1996) or simply green spinel, as named in the literature (e.g. Candia et al. 1991; Franceschelli et al. 2002). Its general formula is [(Al8.36-13.11 Cr0.23-4.38 Fe^{3+}2.40-4,17)16(Mg3.88-7.46 Fe^{2+}0.52-4.09) 8O32]. The compositional zoning (Figure 4), identified under the optical microscope, is given by olive-green rims and dark green to brown centers and is related to chemical variations that occur between these two zones (Table 2). The rims show higher Al_2O_3 contents, whereas the centers are relatively enriched in Cr_2O_3 and, to a lesser extent, in Fe^2O3, evidencing substitution of Cr^{3+} and Fe^{3+} by Al^{3+} towards the crystal centers. The average Mg# at the Cr-spinel rims is 0.86 (varying from 0.77 to 0.93), whereas it is 0.66 in the centers (varying from 0.55 to 0.77), which represents a large compositional variation. The Cr-spinel zoning can be observed in Figure 4, which shows the Cr, Al and Fe distributions along a spinel crystal. The increase of Cr^{3+} and Fe^{3+} and the decrease of Al^{3+} and Mg^{2+} is evident from the rim to the center of the crystal.

METAMORPHISM OF CLÁUDIO ULTRAMAFIC ROCKS

The low Ca contents of orthopyroxene of Cláudio ultramafic rocks indicate total metamorphic re-equilibration of the mineral. During the subsequent metamorphic processes, the Ca amount lost by the original (magmatic) orthopyroxene concentrated in other phases (for example, clinoamphiboles). The recrystallization of the rims of Cr-spinel crystals included in the olivine suggests that it is either a metamorphic or a totally recrystallised igneous olivine. Serpentine and Mg-chlorite reveal a low-grade metamorphic process and show chemical compositions compatible with those of the minerals that originated them. In this sense, the high Al, Fe and Mg contents found in chlorite indicate that it originated from olivine, clinoenstatite and spinel. Serpentine was probably generated from the hydration of olivine during retrograde metamorphism. In general, spinels preserve in their structures a record of the metamorphic events that affected them, and are usually used to solve questions regarding the metamorphic history of their host rocks. Considering that other minerals that constitute the Cláudio metaultramafites are totally recrystallised, the chemical data obtained for the spinels are the most useful to decipher the metamorphic evolution of these rocks. It is possible that the composition of the Cr-spinel centers reflects that of the original magmatic spinel. The rims, on the other hand, were totally recrystallised during the high-grade metamorphism, when part of Cr^{3+} and Fe^{3+} of the original Cr-spinel was replaced by Al^{3+}, transforming it in hercinite (strongly Al-enriched Cr-spinel). This type of zoning was also identified in hercinite (s.s.) generated during the granulite-facies metamorphism that affected the ultramafic amphibolites of northern Sardinia in Italy (Franceschelli et al. 2002). For comparison, these data were plotted together with other Brazilian occurrences (Figure 6), chosen for their similarities with the Sardinian amphibolites (Ribeirão dos Motas Layered Sequence "SARM" [(Carvalho Júnior 2001; Carvalho Júnior & Carneiro 2002); rocks from the Rio Manso region (Pinheiro 1998)] or places where metamorphism was as intense as that that affected the Cláudio metaultramafites (Mangabal I and II Complexes - Candia & Girardi 1985).

It is thus observed in Figure 6 a close correlation between the compositions of the Cr-spinels from the Cláudio metaultramafic rocks and those from SARM, the Rio Manso region and Mangabal I and II Complexes. The composition of the SARM Cr-spinels is very similar to that of the Al-enriched rims of the Cláudio spinels, as well as that of the aluminous spinels from the Mangabal II Complex (Candia & Girardi 1985; Candia et al. 1991). The ferrichromites (spinels characteristic of the greenschist facies) from Mangabal I and II, as expected, plot differently from the other spinels, close to

Table 2 Average composition and standard deviation of the silicate phases of the Cláudio metaultramafic rocks. 1 - Average of 12 points at zoned spinel rims; 2 - Average of 11 points at zoned spinel centers; 3 - Average of 30 points in olivine; 4 - Average of 8 points in serpentine.

Spinel rims			Spinel centers			Olivine			Serpentine		
	Average composition (%)	Standard deviation		Average composition (%)	Standard deviation		Average composit ion (%)	Standard deviation		Average composition (%)	Standard deviation
SiO_2	0.03	0.02	SiO_2	0.03	0.02	SiO_2	38.09	0.69	SiO_2	40.53	3.76
TiO_2	0.03	0.02	TiO_2	0.06	0.03	TiO_2	0.01	0.01	TiO_2	0.13	0.12
Al_2O_3	58.89	3.86	Al_2O_3	43.74	5.11	Al_2O_3	0.01	0.01	Al_2O_3	2.75	2.12
FeO*	4.81	1.65	FeO*	11.27	2.24	FeO	16.71	2.36	FeO	6.65	1.07
Fe_2O_3*	13.25	0.73	Fe_2O_3*	13.98	1.26	MnO	0.01	0.01	MnO	0.07	0.05
Cr_2O_3	6.59	3.16	Cr_2O_3	19.70	4.19	Cr_2O_3	0.21	0.06	Cr_2O_3	0.12	0.11
MnO	0.00	0.00	MnO	0.00	0.00	MgO	44.41	1.93	MgO	36.33	1.44
MgO	17.34	1.31	MgO	12.27	1.74	CaO	0.02	0.02	CaO	0.03	0.01
CaO	0.02	0.02	CaO	0.02	0.01	Na_2O	0.01	0.02	Na_2O	0.00	0.00
ZnO	0.09	0.04	ZnO	0.06	0.03	K_2O	0.01	0.01	K_2O	0.01	0.01
Total	101.06	0.57	Total	101.14	0.61	NiO	0.35	0.15	F	0.04	0.05
Si	**0.01**	0.01	**Si**	**0.01**	0.00	**Total**	**99.83**	0.53	**Total**	**86.64**	**1.00**
Ti	0.01	0.00	Ti	0.01	0.01	Si	0.97	0.01	Si	1.94	0.14
Al	12.37	0.58	Al	9.90	0.88	Ti	0.00	0.00	Ti	0.00	0.00
Fe^{2+}	1.08	0.39	Fe^{2+}	2.74	0.61	Al	0.00	0.00	Al	0.16	0.12
Fe^{3+}	2.67	0.18	Fe^{3+}	3.04	0.32	Fe	0.36	0.05	Fe	0.27	0.04
Cr	0.94	0.46	Cr	3.01	0.71	Cr	0.00	0.00	Mn	0.00	0.00
Mn	0.00	0.00	Mn	0.00	0.00	Mn	0.00	0.00	Cr	0.00	0.00
Mg	6.91	0.39	Mg	5.27	0.61	Mg	1.69	0.06	Mg	2.60	0.14
Ca	0.01	0.01	Ca	0.00	0.00	Ca	0.00	0.00	Ca	0.00	0.00
Zn	0.02	0.01	Zn	0.01	0.01	Na	0.00	0.00	Na	0.00	0.00
Total cations	24.00	-	Total cations	24.00	0.00	K	0.00	0.00	K	0.00	0.00
Soma R^{3+}	15.98	0.00	Soma R^{3+}	15.98	0.01	Ni	0.01	0.00	Total cations	4.97	0.09
Soma R^{2+}	8.02	0.00	Soma R^{2+}	8.02	0.01	Total cations	3.03	0.01	Mg/Mg+Fe	0.91	0.02
$Fe^{2+}/(Fe^{2+}+Mg)$	0.14	0.05	$Fe^{2+}/(Fe^{2+}+Mg)$	0.34	0.08	Fe/(Fe+Mg)	0.17	0.03			
Cr/(Cr+Al)	0.07	0.04	Cr/(Cr+Al)	0.23	0.06	Mg/(Fe+Mg)	0.83	0.03			
$Mg/(Mg+Fe^{2+})$	0.86	0.05	$Mg/(Mg+Fe^{2+})$	0.66	0.08						

the Fe apex. Because ferrichromites have not been found in Cláudio rocks, it is our belief that the Cr-spinel was not affected by low-grade metamorphic processes. A possible explanation is that, being inside the orthopyroxene crystals, Cr-spinel was preserved from low-grade metamorphic re-equilibration. In Figure 6 it is observed that the trend defined by the spinels from the Rio Manso region is similar to that obtained for the Cláudio metaultramafites, but with a dislocation towards the Cr vortex, indicating that the metamorphism at Rio Manso was of a lower grade than that observed in the study area.

PETROGENETIC EVOLUTION OF CLÁUDIO METAULTRAMAFIC ROCKS

One of the reasons that motivated this study was the question whether a relict magmatic mineral phase (e.g. orthopyroxene, olivine, etc.) could be preserved within the present metamorphic paragenesis of the Cláudio metaultramafic rocks, once relict cumulatic textures are frequently found. Thus, mineral chemistry was carried out using the main constituents of the Cláudio metaultramafic rocks, and the results obtained allowed to trace their probable petrogenetic evolution. In principle, it is possible to consider that the magmatic paragenesis of these rocks was composed of orthopyroxene + hornblende + magnesian olivine + Cr-spinel + sulfide. This paragenesis is commonly observed in greenstone belt-type sequences or in layered mafic-ultramafic complexes (e.g. Bushveld, Barbeton, etc.) which were not metamorphosed or underwent low-grade metamorphism. Macroscopically, the banding observed in these rocks characterizes their relict igneous layering. As the relict textures show, some of the minerals (e.g. orthopyroxene, Cr-spinel and olivine) constituted cumulatic phases. It is not possible to state with certainty what constituted the intercumulus material; it may have been clinopyroxene, now totally

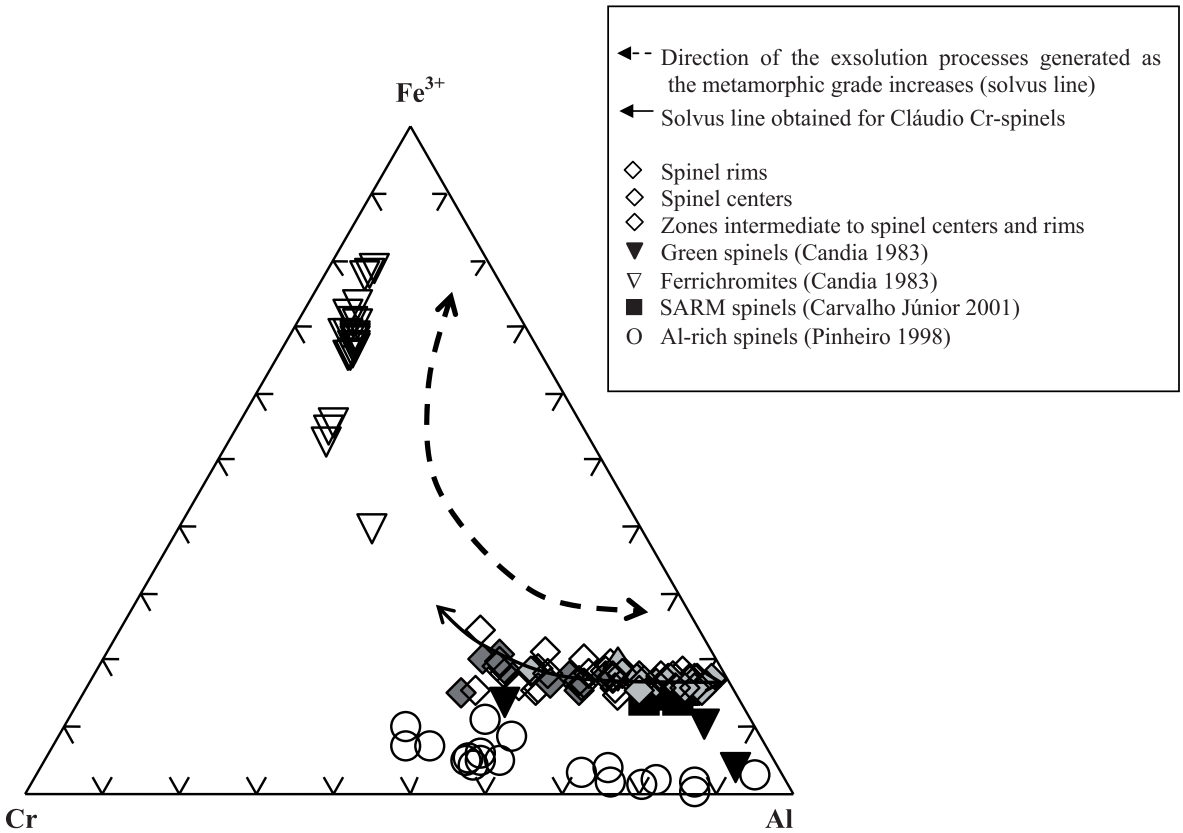

Figure 6: Diagram relating the chemical compositions of the spinels with the metamorphic grade that affected them (based on Sack & Ghiorso 1991).

replaced by secondary minerals (e.g. calcic amphiboles), or even a calcic amphibole (e.g. igneous hornblende). This magmatic protolith underwent a complex crustal petrogenetic evolution, which was started by a high-grade metamorphic event (granulite to upper amphibolite facies) responsible for the metamorphic re-equilibration of the original paragenesis. The retrograde metamorphic process to the greenschist facies generated hydrated minerals, formed at low temperatures. The path of the mineral reactions was the following: 1) magnesian hornblende becomes unstable under low temperatures and starts to be replaced by actinolite; 2) the same happens with olivine, which is strongly susceptible to hydrothermal alteration and low-grade metamorphism. The alteration mechanism involves hydrogen diffusion inside the crystalline structure, where the temporary fixation of such ion liberates Mg, Fe^{2+} and Si, allowing their replacement for Fe^{3+}, Al and Ca (Deer et al. 1996, Wicks & Whittaker 1977). Serpentinization in the most common form of olivine alteration, according to the reaction: $3Mg_2SiO_4$ (forsterite) + $4H_2O$ + SiO_2 = $2Mg_3Si_2O_5(OH)4$ (serpentine), described by Deer et al. (1996). Regionally, the mineral composition and textures of the Cláudio metaultramafites are similar to those described in the Ribeirão dos Motas Layered Sequence (SARM) by Carvalho Júnior (2001) and Carvalho Júnior & Carneiro (2002), thus indicating a cumulus-type magmatic crystallization in a plutonic to sub volcanic environment. However, the occurrence of quartzite lenses and iron formation associated with the Cláudio metaultramafites indicates a volcanic to sub volcanic origin in greenstone belt-type environments. In this case, it is likely that the Cláudio metaultramafites correlate better with the Rio das Velhas Supergroup, which is conspicuously distributed in the Quadrilátero Ferrífero and as isolated occurrences in neighboring regions. At the base of the Rio das Velhas Supergroup the Quebra Ossos Group occurs, constituted by mafic and ultramafic rocks (e.g. komatiites), Algoma-type iron formation, metacherts, and in lesser proportions, volcaniclastic rocks. According to Sichel & Valença (1983), the original constituents of the Quebra Ossos Group are peridotitic komatiites, metamorphosed to the greenschist facies. They present locally typical igneous structures (pillow lavas) and spinifex texture.

CONCLUSIONS

The studies focusing the metaultramafites from the Cláudio region evidenced the superimposition of metamorphic events on the magmatic paragenesis. The metamorphic processes occurred in two stages. In the first, the magmatic paragenesis underwent high-grade metamorphic conditions (granulite to upper amphibolite facies), causing the total and/or partial recrystallization of its minerals. In the second, with hydration of this paragenesis and the drop of temperature, part of the pyroxene and olivine were replaced by amphiboles, talc and Mg-chlorite. The substitution of magnesian hornblende for actinolite suggests that the retrograde metamorphism reached the greenschist facies. On the other hand, the mineral composition and textures of the Cláudio metaultramafites are similar to those described in SARM by Carvalho Júnior (2001) and Carvalho Júnior & Carneiro (2002) indicating a cumulus-type magmatic crystallization in a plutonic to sub volcanic environment. However, the occurrence of quartzite lenses and iron formation associated with the Cláudio metaultramafites indicates a volcanic to sub volcanic origin in greenstone belt-type environments. Typically, komatiitic flows present volcanic textures (e.g. spinifex) or structures (e.g. pillows) at the top, and plutonic (cumulatic) textures at the base, as those described by Barnes (1985) in the Abitibi Greenstone Belt (Canada) and by Arndt et al. (1977) in Munro Township (Ontario). Typical volcanic textures or structures have not been identified in Cláudio metaultramafites. Considering the intense weathering that affected the study region and the rarity of preserved outcrops, these structures may have been variably obliterated. On the other hand, relict plutonic textures are always present in the Cláudio metaultramafic rocks, despite the complete transformation of the magmatic paragenesis by metamorphic processes. Thus, as a tectono-stratigraphic hypothesis, to be further proved by more detailed studies, the Cláudio metaultramafites are correlated with the Rio das Velhas Supergroup.

ACKNOWLEDGEMENTS

The authors thank the Fundação de Amparo a Pesquisa de Minas Gerais (Fapemig) for financial support for Research Projects CRA 619/04, to Lopag – Laboratório de Preparação de Amostras para Geoquímica e Geocronologia and lamin – Laboratório de Laminação (both from Degeo/EM/UFOP) and LMA - Laboratório de Microanálises from Defis/IF/UFMG. And finally thanks to CPNq for grants to author (MAC).

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(Footnotes)

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