XV Congreso Peruano de Geología. Resúmenes Extendidos.
Sociedad Geológica del Perú, Pub. Esp. N° 9 (2010), Cusco p. 87-90

HIGH PRESSURE METAMORPHIC CONDITIONS IN GARNET AMPHIBOLITE FROM A COLLISIONAL SHEAR ZONE RELATED TO THE TAPO ULTRAMAFIC BODY, EASTERN CORDILLERA OF CENTRAL PERU

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INTRODUCTION AND SETTING

A discontinuos belt of elongated ultramafic rock bodies (mostly serpentinites) occurs in the Eastern Cordillera of the central Peruvian Andes. One of the main occurrences is the Tapo Massif, a lense-shaped serpentinite body, ~2 km x 5 km, comprising small podiform chromitite deposits (Castroviejo et al., 2009) and bands or lenses of garnet-amphibolite, both strongly sheared and thrust upon the upper Paleozoic sediments of the Ambo Group (Fig. 1). Metabasite geochemistry suggests a mid-ocean ridge or an ocean island protolith. The whole sequence can be interpreted as a disrupted ophiolitic complex (Castroviejo et al., 2010). The geological setting of the Tapo occurrence is described by J.F. Rodrigues et al. (2010). To get information about its geotectonic setting we applied new geothermobarometric techniques to the garnet amphibolite. Finding representative samples with an adequate mineralogy to apply these techniques is in this case a difficult task. A common problem is the almost ubiquitous overprinting by serpentinisation or retrograde metamorphism and, locally, by metasomatism or alteration enhanced by deformation, producing a variety of rock types, as rodingites, birbirites and listvaenites. Nevertheless, careful sampling followed by petrographic examination of the rocks allowed to identify some samples in which useful assemblages are present.

ASSEMBLAGES AND MINERAL CHEMISTRY

We selected three garnet amphibolite samples[1] (090606-2, 090606-3 and 270607-7, Fig. 1) which contain the assemblage garnet-Ca-amphibole-epidote-chlorite-albite-quartz-titanite-ilmenite. Additionally clinopyroxene is present in sample 090606-3. This assemblage points to conditions of the albite-epidote amphibolite facies.

Garnet is essentially an almandine-grossular solid solution ($almandine_{0.46-0.62}grossular_{0.25-0.45}pyrope_{0.01-0.18}spessartite_{0.02-0.11}$). Almandine and pyrope contents increase from core to rim, whereas spessartite decreases and grossular contents show little variations. Amphibole compositions vary strongly between samples: in sample 090606-3 amphibole is actinolite to magnesiohornblende (Na 0.10-0.66 apfu, Na_A 0.0-0.66 apfu, X_{Mg} 0.42-0.68), in sample 270607-7 magnesiohornblende to tschermakite (Na 0.58-1.03 apfu, Na_A 0.36-0.82 apfu, X_{Mg} 0.25-0.46) and in sample 090606-2 tschermakitic hornblende to tschermakite (Na 0.05-0.80 apfu, Na_A 0.3-0.5 apfu, X_{Mg} 0.41-0.58). Epidote composition within all samples varies strongly ($X_{pistacite}$=0.4-0.9) contrasting that of chlorite (Si 5.3-5.7 apfu; X_{Mg} 0.35-0.51). Clinopyroxene composition is $diopside_{0.56-0.58}hedenbergite_{0.20-0.30}acmite_{0.07-0.10}orthopyroxene_{0.02-0.05}tschermak\ component_{0.02-0.07}$. Plagioclase is invariably albite.

GEOTHERMOBAROMETRY

We calculated pseudosections for the three metabasite samples using the PERPLE_X software package (Connolly 2005). The thermodynamic data set of Holland & Powell (1998, updated 2002) for minerals and aqueous fluid was used. Calculations were performed using the following solid-solution models: for epidote, garnet, plagioclase, clinopyroxene, omphacite, amphibole and chlorite by Holland

& Powell (2003) and Powell & Holland (1999). For the calculation of the pseudosections the major element compositions analysed by XRF were simplified to a 9-component system (SiO_2-TiO_2-Al_2O_3-FeO-MgO-CaO-Na_2O-H_2O-O_2) normalized to 100% (Table 1). Water contents were augmented to excess water conditions that are considered to have prevailed during peak PT-conditions. Oxygen contents were arbitrarily chosen to account for epidote and Fe^{3+}-rich clinopyroxene present in the samples. Calculated compositions of minerals provide good coincidence with measured ones (Table 2) except partly for amphibole, because solid solution models for amphibole are still not optimal.

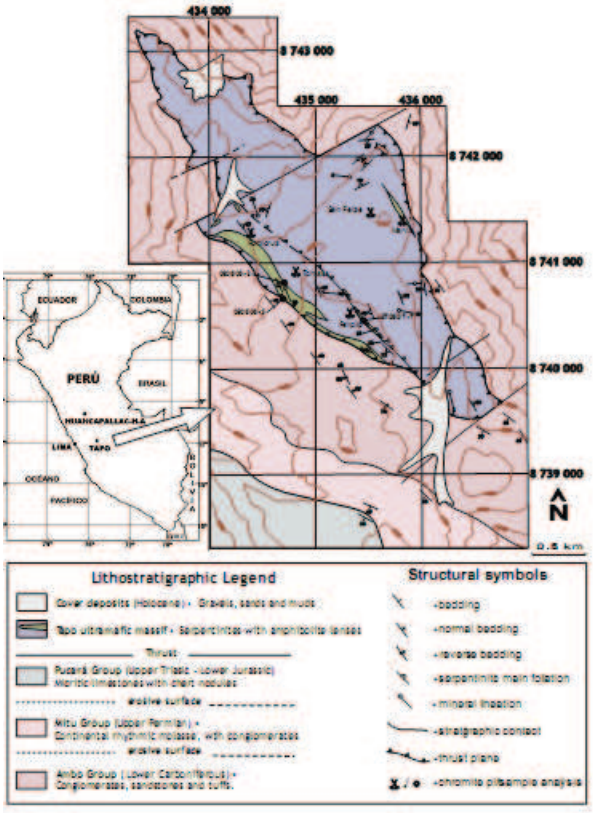

Fig.1. Geological map of the Tapo Ultramafic Complex with indications of the sample localities.

We simplified the pseudosections to present mere stability fields in the PT-range 400-600°C, 6-15 kbar in Fig.2. Garnet appears in the metabasite at conditions exceeding 8 kbar and 520°C. Whereas chlorite, epidote and Ca-amphibole are mostly stable in the considered PT-range, titanite is replaced at temperatures >520°C by ilmenite or rutile (>10 kbar). Albite is stable up to 520°C, 9 kbar and is partly replaced by plagioclase at higher temperature. Fe^{3+}-rich clinopyroxene is stable up to about 7 kbar, 450°C and 12 kbar, 550°C, whereas omphacite was not formed under the considered conditions and compositions according to our calculation.

The assemblages representing peak metamorphic conditions coincide for all three selected samples within a range of 525-575°C, 11-14 kbar, more restricted for sample 090606-2 at 12-13 kbar, 530-540°C. Chlorite, albite and ilmenite are considered as retrograde phases in sample 090606-3, as albite, quartz and titanite in sample 270607-7 and albite in sample 090606-2.

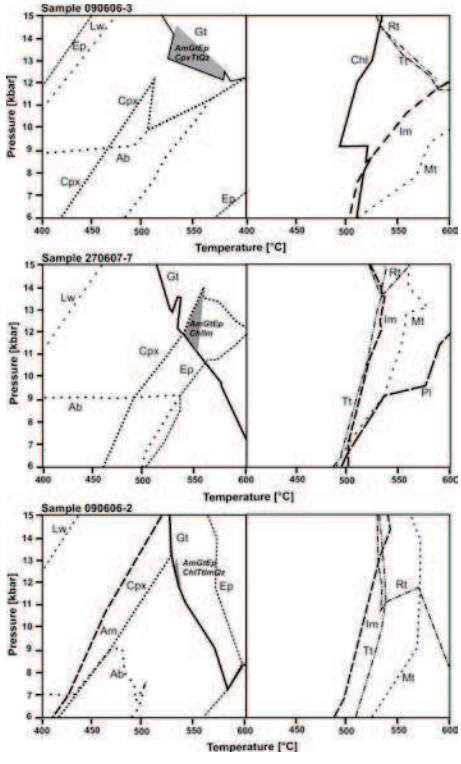

Fig.2 Stability fields of minerals deduced from PT-pseudosections calculated from whole rock compositions (Table 1) in the system SiO2-TiO2-Al2O3-FeO-MgO-CaO-Na2O-H2O-O2. Grey fields represent the stability field of the assemblages in the respective samples which represent peak PT-conditions. Abbreviations: Ab-albite, Am-Ca-amphibole, Chl-chlorite, Cpx-clinopyroxene, Ep-epidote, Gt-garnet, Im-ilmenite, Lw-lawsonite, Mt-magnetite, Pl-plagioclase, Rt-rutile, Tt-titanite.

CONCLUSIONS

We can restrict the peak metamorphic conditions for the Tapo Ultramafic Complex to 12.5±1 kbar and 535±20°C corresponding to 41-48 km burial depth (calculating with a mean crustal density of 2.8 g/ccm) and a low metamorphic geotherm of 10-13°C/km. Such conditions occur in subduction settings and collisional belts. Similar conditions were derived e.g. by Massonne & Calderón (2008) in a Devonian collision zone between an exotic microplate ("Chilenia") and the South America. A comparable situation might also be conceivable for the situation in the Eastern Cordillera of Peru.

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TABLE 1

(a) Whole rock compositions of metabasite

(wt-%)	090606-3	090606-2	270607-7
SiO2	49,43	40,01	40,35
Al2O3	11,55	10,11	10,99
Fe2O3	14,13	21,86	23,35
MnO	0,15	0,18	0,25
CaO	10,84	8,11	8,88
MgO	6,80	7,96	6,82
Na2O	3,06	0,22	1,97
K2O	0,12	0,06	0,12
TiO2	2,57	3,26	5,09
P2O3	0,13	0,01	<0.050
LOI	1,03	8,03	2,18
Sum	99,81	99,81	99,99

(b) Simplified compositions used for calculations of the pseudosections

(wt-%)	090606-3	090606-2	270607-7
SiO2	47,28	41,51	39,30
Al2O3	11,05	10,49	10,70
FeO	12,18	20,43	20,49
MnO	0,14	0,19	0,24
CaO	10,37	8,41	8,65
MgO	6,50	8,26	6,65
Na2O	2,93	0,23	1,92
TiO2	2,46	3,38	4,95
H2O	7,00	7,00	7,00
O2	0,10	0,10	0,10
Sum	100,00	100,00	100,00

Table 2 Representative mineral analyses and mineral compositions calculated with PERPLE_X for comparison

Clino-pyroxene	090606-3	090606-3	Garnet	090606-3c	090606-3r	090606-3	090606-2r	090606-2	270607-7c	270607-7r	270607-7
SiO2	50.30	calc	SiO2	36.34	36.75	calc	38.29	calc	36.44	36.14	calc
Al2O3	1.43	523 C/ 13.1	Al2O3	21.04	21.04	523 C/ 13.1	21.75	533 C/ 12.35	21.07	21.11	540 C/ 11.90
TiO2	0.17	liaz	TiO2	0.15	0.15	liaz	0.04	liaz	0.17	0.12	liaz
Fe2O3	3.54		Fe2O3	0.58	0.53		0.00		0.42	0.99	
FeO'	7.14		FeO'	21.28	23.42		22.85		25.42	24.84	
MnO	0.09		MnO	4.39	0.94		0.30		4.24	2.27	
MgO	11.84		MgO	0.32	1.13		0.47		0.35	0.51	
CaO	24.14		CaO	14.28	14.18		14.11		10.77	11.17	
Na2O	0.34		Sum	98.38	98.34		100.52		99.48	99.50	
Sum	99.74		Si	5.891	5.918	6.000	6.000	6.000	5.892	5.844	6.000
Si	1.921	2.000	Al	0.109	0.082		0.000		0.108	0.156	
Al	0.073		SUM	6.000	6.000		6.000		6.000	6.000	
SUM	1.994		Al	3.912	3.917	4.000	4.017	4.000	3.904	3.845	4.000
Al	0.000	0.140	Fe3+	0.071	0.045		0.000		0.077	0.120	
Ti	0.005		Ti	0.018	0.018		0.007		0.021	0.015	
Fe3+	0.101		SUM	4.000	4.000		4.023		4.000	4.000	
Fe2+	0.227	0.440	Fe2+	2.824	3.183	3.450	2.994	3.450	3.435	3.430	3.740
Mn	0.003		Mn	0.403	0.128		0.104		0.443	0.311	
Mg	0.468	0.320	Ca	2.420	2.448	2.320	2.704	2.100	1.842	1.934	2.020
Ca	0.978	0.840	Mg	0.078	0.272	0.230	0.177	0.220	0.024	0.194	0.240
Na	0.025	0.140	SUM	6.044	6.032	6.000	5.961	6.000	6.044	6.071	6.000
SUM	2.004	2.000	Andr	0.012	0.011		0.000		0.012	0.020	
O	6.000		Gros	0.399	0.395	0.387	0.454		0.294	0.299	
Tcpx	0.007		Spes	0.100	0.021		0.018		0.110	0.071	
Mcpx	0.003		Pyro	0.013	0.045	0.038	0.026		0.014	0.032	
Tj	0.048		Alm0	0.477	0.528	0.577	0.502		0.568	0.598	
Acm	0.101		Cations based on 48 negative charges including 10 cations in the tetrahedral								
Opx	0.047		and octahedral site to calculate Fe3+; c core, r rim								
Hed	0.197										
Dep	0.520		Chlorite	270607-7	270607-7	090606-2	090606-2	090606-3			
XFe	0.253										
XFe3	0.308		SiO2	24.44	calc	25.87	calc	24.99			
			Al2O3	17.90	540 C/ 11.90	20.34	533 C/ 12.35	19.18			
			TiO2	0.07	liaz	0.02	liaz	0.01			
			FeO	31.99		28.45		28.61			
			MgO	12.43		12.73		12.88			
			MnO	0.35		0.34		0.38			
			CaO	0.15		0.04		0.03			
			Na2O	0.07		0.00		0.00			
			H2O'	11.18		11.22		10.98			
			Sum	100.60		99.27		97.52			
			Si	5.475	5.940	5.524	5.940	5.459			
			Al	2.325	2.040	2.476	2.040	2.541			
			Alt	2.203	2.040	2.472	2.040	2.503			
			Ti	0.012		0.003		0.001			
			Mn	0.064		0.062		0.070			
			Fe	5.743	5.900	5.120	5.740	5.228			
			Mg	3.979	3.900	4.055	4.220	4.197			
			Sum	12.000	12.000	11.891	12.000	11.999			
			Na	0.028		0.000		0.000			
			Ca	0.034		0.014		0.018			
			OH	16.000	16.000	16.000	16.000	16.000			
			Cations based on 14 negative charges; H2O calculated on the basis of OH=16								

Amphi-bole	270607-7	270607-7	090606-2	090606-2	090606-3	090606-3
SiO2	40.68	calc	44.29	calc	42.70	calc
Al2O3	14.18	540 C/ 11.90	9.57	533 C/ 12.35	13.47	523 C/ 13.1
TiO2	0.23	liaz	0.18	liaz	0.05	liaz
Fe2O3	4.96		4.47		3.21	
FeO'	20.14		13.59		12.77	
MgO	4.49		9.79		13.52	
CaO	10.59		10.84		11.75	
BaO	0.00		0.01		0.02	
K2O	0.23		0.07		0.05	
Na2O	3.08		1.75		0.87	
MnO	0.10		0.19		0.18	
H2O'	1.97		2.01		2.09	
Sum	100.24		96.95		100.88	
Si	6.204	7.144	6.591	7.540	7.57	7.521
Ak	1.794	0.856	1.409	0.460	0.427	0.479
Sul	8.000	8.000	8.000	8.000	8.000	8.000
Ak	0.755	0.956	0.570	0.420	0.194	1.259
Ti	0.027		0.020		0.006	
Mn	0.013		0.023		0.022	
Fe3+	0.569		0.523		0.345	
Fe2+	2.570	2.150	1.692	2.390	1.535	1.500
Mg	1.047	1.823	2.172	2.150	2.594	1.941
Su2	13.000	13.000	13.000	13.000	13.000	13.000
Ca	1.731	1.715	1.729	1.920	1.510	1.131
Ba	0.000		0.001		0.001	
Na	0.910	0.750	0.504	0.200	0.243	0.940
K	0.044		0.013		0.009	
Su3	2.484	2.305	2.244	2.120	2.043	2.091
OH	2.000	2.000	2.000	2.000	2.000	2.000
Proportion of cations, r based on the sum of cations = 13 except for Ca, Na and K for estimation of Fe3+ and on 46 negative charges						

Epidote	270607-7	270607-7	090606-2	090606-2	090606-3	090606-3
SiO2	38.14	calc	37.46	calc	37.98	calc
Al2O3	28.18	540 C/ 11.90	28.33	533 C/ 12.35	23.53	523 C/ 13.1
Fe2O3	7.49	liaz	7.27	liaz	13.19	liaz
Mn2O3	0.05		0.04		0.01	
TiO2	0.11		0.10		0.09	
CaO	23.79		23.32		23.48	
H2O'	1.91		1.87		1.90	
Sum	99.94		98.41		100.44	
Si	3.000	3.000	3.000	3.000	3.000	3.000
Al	2.611	2.320	2.674	2.400	2.190	2.520
Ti	0.006		0.006		0.005	
Mn	0.003		0.002		0.001	
Fe	0.455	0.420	0.438	0.400	0.784	
SUM	3.074	3.000	3.122	3.000	2.981	0.480
Ca	2.003	2.000	2.001	2.000	2.004	3.000
SU2	2.005		2.001		2.003	
OH	1.000	1.000	1.000	1.000	1.000	1.000
O'	12.123	12.000	12.187	12.000	11.980	12.000
Proportions of cations are based on normalization of 3 to three cations						