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Integrated Log Interpretation in the Chinese Continental Scientific Drilling Main Hole (Eastern China): Lithology and Mineralization

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Abstract: Delineation of lithology and mineralization of different rock units of the Chinese Continental Scientific Drilling Main Hole (CCSD-MH), Eastern China, is the main objective of this study. Different logging operations were conducted in the studied area. Subduction and metamorphism lead to high compressional wave velocity (Vp) and low neutron density (CNL) values of different rocks. Eclogites and ultramafics show high bulk density (DEN) and photoelectric index (Pe) values, due to their high content of heavy and basic minerals. Gneisses are more radioactive (GR) and resistive (RD), since they have high feldspar content. Serpentinization causes in high CNL values of ultramafics. Retrogression of eclogites to amphibolite facies detected from the general decrease of DEN, Pe, Vp and RD and increase of GR and CNL values. This is mainly due to the secondary alteration and break down of heavy and basic minerals to retrograde materials such as amphibole, mica, zoisite and quartz during exhumation process. Shearing of paragneisses lowers their Vp values. Generally mineralization increases DEN, Pe of eclogites and decreases their GR value and decreases DEN, Pe of the gneisses and increases their GR readings.

Key words: Chinese continental scientific drilling main hole, ultrahigh-pressure metamorphic rocks, retrogression of eclogites, well logging

INTRODUCTION

The Dabie-Sulu metamorphic belt is one of the largest recognized ultrahigh-pressure (UHP) metamorphic belts in the world. The belt is formed by the Triassic collision of the Sino-Korean and Yangtze cratons with the peak metamorphic age of 220-245 Ma (Hacker *et al.*, 1998; Rowley *et al.*, 1997). The collision zone is about 1000 km long. The belt is offset by the Tanlu Fault and displaced northward approximately 530 km to the Sulu region (Zhang *et al.*, 1995). The Sulu terrane in the east is segmented into a number of blocks by several NE-SW-trending faults sub-parallel to the Tanlu fault (Zheng *et al.*, 2003).

The Chinese Continental Scientific Drilling Main Hole, CCSD-MH, is located in the southern part of this belt (N34.33° E118.7°), about 30 km east of the Tanlu fault, 70 km west of the Yellow sea and 17 km southwest of Donghai County (Fig. 1) (Zhang *et al.*, 2006).

All of the supracrustal rocks of the Sulu-Dabie UHP terrane have experienced deep subduction and rapid exhumation (Liou *et al.*, 2000; Liu *et al.*, 2002). Coesite inclusions have been found in core samples of the CCSD-MH, providing evidence that these country rocks experienced UHP metamorphism with peak temperatures at 754-805°C and pressure >2.8 GPa (Liu *et al.*, 2002).

The core log analysis, after reorientation of cores (Zou *et al.*, 2007), indicates that the lithology of the CCSD-MH is very complex (Fig. 2). It consists mainly rutile eclogite, phengite eclogite, retrograded eclogite, garnet amphibolite, amphibolite, ultramafic rock, garnet biotite plagioclase gneiss, epidote plagioclase gneiss, granitic gneiss (Liu *et al.*, 2004, 2005; You *et al.*, 2004; Zhang *et al.*, 2000a). P- and S-wave velocities measured at 600 MPa vary from 5.08 to 8.64 km sec^{-1} and 2.34 to 4.93 km sec^{-1}, respectively (Kern *et al.*, 2002). Densities are in the range from 2.60 to 3.68 g cm^{-3} (Kern *et al.*, 2002; Luo *et al.*, 2007).

Eclogites are coarse-grained greenish rocks consisting primarily of garnet, mainly pyrope and sodic pyroxene, omphacite and phengite, kyanite, quartz and rutile as accessory minerals. The contents of garnet and omphacite are from 85-90% in fresh eclogite and fully retrograded eclogite has been transformed to epidote amphibolite (Liu *et al.*, 2007). They are found as layers or lenses in gneisses of the amphibolite facies. Most of eclogite layers contain thin bands of paragneiss, orthogneiss and amphibolite-retrograded eclogite (Liu *et al.*, 2004). A number of unusually mineralogical

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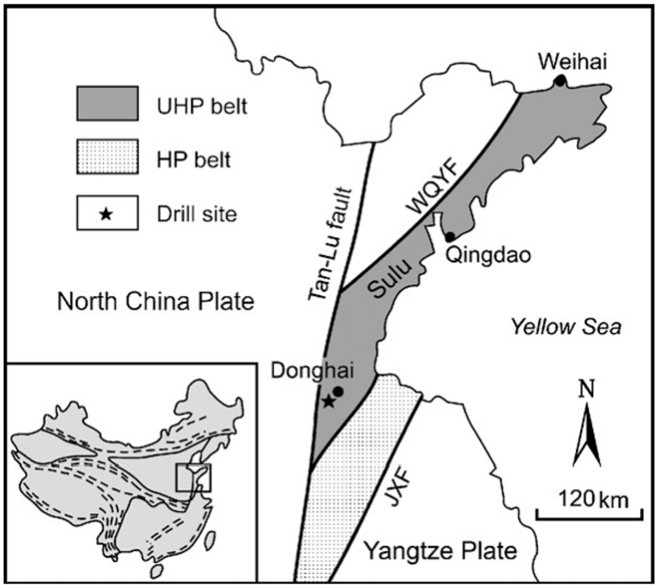

Fig. 1: Simplified geological map of the Sulu UHP metamorphic belt showing major tectonic units and location of the CCSD-main drill hole WQYF = Wulian-Qingdao-Yantai fault, JXF = Jiashan-Xiangshui fault (Zhang *et al.*, 2006)

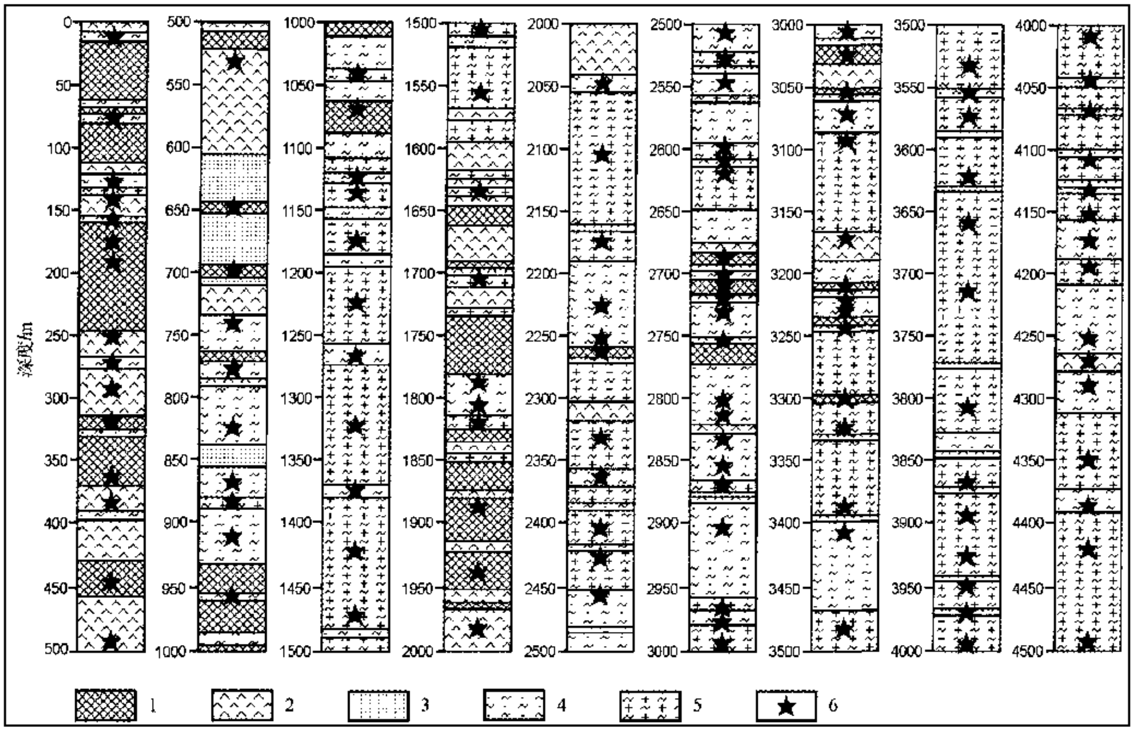

Fig. 2: The complex lithology of (0-4500 m) CCSD-MH from core log description. 1 refers to eclogite, 2 is for retrograded eclogite and amphibolite, 3 is ultramafic, 4 and 5 are para- and ortho-gneisses respectively and 6 is sampling locations (After Liu *et al.*, 2005)

findings have been made lately from the UHP rocks, including native titanium inclusions in garnet of eclogite (Chen *et al.*, 2000).

Amphibolites are medium- to coarse-grained, highly foliated and schistosed rocks found as inclusions and layers in gneisses and eclogites. They are resulted from ductile shearing which cause in displacement, retrogression and detachment of original rock sheets during subduction and exhumation. The amphibolite facies overprinted the earlier UHP metamorphism during late exhumation within the crust at 180-210 Ma (e.g., Hacker *et al.*, 1998; Liu *et al.*, 2003). They mainly consist of hornblende and plagioclase and some garnet, pyroxene and biotite.

Ultramafics are mantle material (227 ma) brought to the surface in association with eclogites and gneisses, during exhumation process. They mainly consist of olivine, pyroxene and garnet. But many of the rocks are intensely serpentinized and chloritized, especially near the upper and lower contacts with amphibolite, eclogite and paragneiss (Liu *et al.*, 2004; Salim *et al.*, 2007). It is commonly assumed that some of the garnet peridotites were directly trapped by exhumed slab from the mantle, the others were emplaced earlier to crustal levels from the mantle and then subducted together with supracrustal rocks to mantle depths again to suffer UHP metamorphism (e.g., Tsai *et al.*, 2000; Yang and Jahn, 2000; Zhang *et al.*, 2000b).

Orthogneisses are medium to coarse-grained rocks consisting mainly of K-feldspar, quarts and plagioclase as major minerals and biotite, amphibole, phengite, epidote, garnet and magnetite, which are secondary and accessory minerals. They represent the main country rock hosting the eclogites. They have undergone amphibolite facies retrograde metamorphism (Liu *et al.*, 2002). From geochemical analysis the SiO_2 and Al_2O_3 contents are 71.55-77.18 and 11.54-13.38 wt. %, respectively. These rocks contain very low abundances of $FeO+Fe_2O_3$ (1.05-2.94 wt. %), MgO (0.14-0.59 wt. %), CaO (0.30-2.65 wt. %) and TiO_2 (0.15-0.31 wt. %) and relatively low K_2O (4.35-5.56 wt. %). They have relatively low Sr contents (36.10-114 ppm), but are highly enriched in Rb (62.80-277 ppm) and Th (8.73-23.90 ppm) (Liu *et al.*, 2004). There is low Al-titanite mineralization in jadeite-bearing gneisses (Ye *et al.*, 2002).

Paragneisses occur as thin layers, bands, or stripes within eclogites and orthogneisses. At lower depths they show clear foliation and regularly-spaced jointing (Salim *et al.*, 2007). Thick beds of paragneisses are sheared by eclogites or ultramafics. They mainly composed of plagioclase, quartz, k-feldspar, epidote, biotite and minor garnet, hornblende, ilmenite and phengite (Liu *et al.*, 2004). Like orthogneisses they are light colored medium to coarse-grained and highly foliated, sheared and mylonized. From seismic and core studies, the average density of gneisses in the Sulu area is 2600-2700 kg m^{-3}, seismic velocity 5900-6400 m sec^{-1} (Yang *et al.*, 2005b).

This study presents a state-of-the-art review on well log behavior of the UHP metamorphic rocks in the Dabie-Sulu orogen by integrating the existing data together with our partially unpublished data. The main purposes of the research are to differentiate between different rock units, providing the lithology of the whole 5140 m from continuous different well logs, which is difficult and expensive to be done by coring and other methods, to delineate the unclear boundary, during core analysis, between fresh eclogite and eclogite retrograded to amphibolite and study the effect of mineralization upon criteria of different rocks.

MATERIALS AND METHODS

From June 2001 to January 2005, China drilled a 5140 m deep Chinese Continental Scientific Drilling Main Hole (CCSD-MH), at the southern part of the Sulu ultra-high pressure metamorphic (UHPM) belt.

CCSD well logging project carried out 7 integrated logging runs at the depth intervals of 100-530, 530-1200, 1200-2046, 2046-3000, 3000-3580, 3580-4400 and 4400-5140 m. Different logging operations were conducted within the CCSD-MH, including the records of caliper, acoustic, reading P-wave travel time and consequently its velocity, Vp, in km sec^{-1}, electric, including different resistivities, RD, RS, RSFL, in ohm m, nuclear, including Gamma Ray (GR) in API units, uranium (U) and thorium (Th) content in ppm, Potassium (K) content in %, neutron porosity (CNL) in p.u., bulk density (DEN) in g cm^{-3}, effective photoelectric absorption capture cross section(Pe) in b/e, magnetic, temperature, geometric, geochemical and borehole image data.

These logs were recorded by Shengli logging company using an ECLIPS-5700 imaging log unit of Atlas Company.

At the depth interval of 2900-3600 m the borehole was reamed because of the instability of sidewall and mud containing barite is used at the depth interval of 2900-3700 m.

Core log descriptions (Yang *et al.*, 2005a), tests on core samples (Liu *et al.*, 2004), seismic and geological information, used for geophysical well log calibration so as to differentiate between rock types, their mineralogy and their approximate depths. Since the structure of the area is so complex, including faulting, fracturing, shearing, etc., representative data samples were used for different analysis. Statistical mean values of different well log measurements are calculated.

RESULTS AND DISCUSSION

In different crossplot diagrams (Fig. 3), data qualitatively clustered into five separate fields representing different lithologies in the study area. Table 1 show that the highest DEN, Pe values are those of eclogites, ultramafics and amphibolites and the lowest values are those of gneisses. Vp of eclogites and amphibolites is the highest, followed by those of orthogneisses and ultramafics, while that of paragneisses is the lowest.

CNL values of ultramafic rocks are extremely higher than those of gneisses and eclogites.

Gneisses, amphibolites and eclogites are highly resistive, while the resistivity of ultramafics is the lowest.

Th- and K-content of gneisses is so high and this reflect their extremely high GR readings, ultamafics and eclogite have low Th- and K-content and consequently low GR values.

Orthogneiss's GR, Vp and RD values are higher than those of paragneisses.

High DEN, Vp and RD values of eclogites are due to their high content of rutile and low content of quartz, amphibole and zoisite. Their lack of feldspar lowers their GR readings (Fig. 3a).

There is direct proportionality between Vp and DEN values. For eclogites the relationship between Vp and density is best fit by:

$$Vp = -4.754+3.502\rho \quad \text{at } 50 \text{ MPa},$$

and

$$Vp = -2.747+3.095\rho \quad \text{at } 600 \text{ MPa}$$

where, Vp in km sec^{-1}ec and ρ is the density in g cm^{-3} (Wang *et al*., 2005).

Acidic origin of gneisses and consequent high feldspar content, increases their GR and RD values (Fig. 3a, d). Gneisses show low DEN and Pe because of

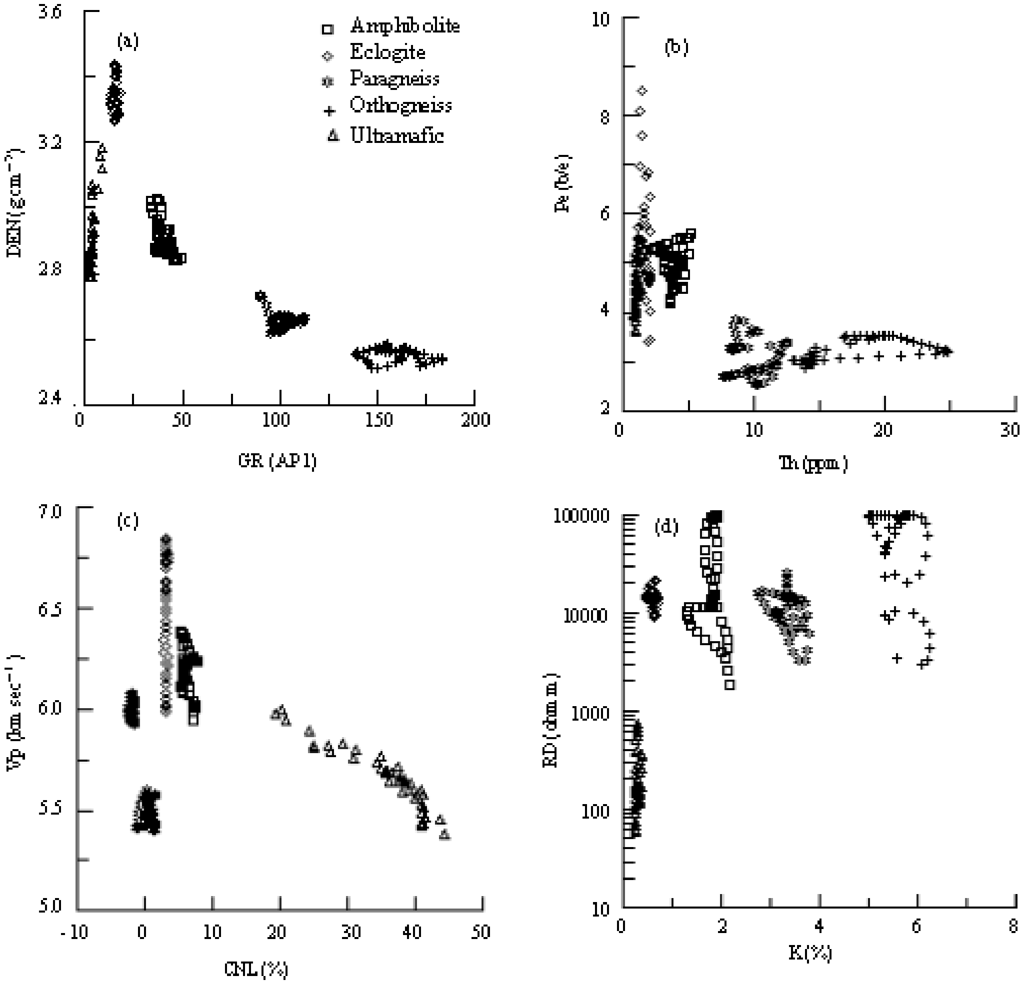

Fig. 3: Cross plots of different log responses of UHP metamorphic rocks of CCSD-MH

Table 1: Statistical mean value ± standard deviation of different log measurements of UHP metamorphic rocks (N is number of data points)

Term	N	GR (API)	U (ppm)	TH (ppm)	K (%)	Vp (km sec^{-1} ec)	DEN (g cm^{-3})	Pe (b/e)	CNL (%)	RD (Ω m)
Ultramafic	97	4.74±2.0	0.46±0.07	0.85±0.16	0.30±0.06	5.72±0.19	2.93±0.08	4.30±0.42	37.94±3.67	429.45±859.3
Eclogite	50	15.41±1..36	0.55±0.08	1.45±0.35	0.58±0.07	6.52±0.26	3.33±0.05	5.35±1.00	3.06±0.11	14338.08±2920.2
Amphibolite	50	40.22±3.15	0.28±0.11	3.65±0.75	1.78±0.22	6.18±0.10	2.91±0.05	5.01±0.35	6.12±0.75	30506.83±32690.5
Paragneiss	145	100.96±11.00	0.36±0.23	8.58±1.91	3.53±0.58	5.43±0.23	2.68±0.05	3.30±0.41	0.82±1.12	13701.32±14718.0
Orthogneiss	481	158.69±16.91	1.92±1.24	20.28±4.35	5.3±0.47	5.96±0.12	2.55±0.05	3.22±0.27	-1.37±0.57	41827.94±40885.1

Table 2: Eclogite types and its retrogression effect on different log responses (Mean ±SD; N is number of data points)

Term	N	GR (API)	U (ppm)	TH (ppm)	K (%)	Vp (km sec^{-1} ec)	DEN (g cm^{-3})	Pe (b/e)	CNL (%)	RD (Ω m)
Rutile Eclogite	50	15.41±1.36	0.55±0.08	1.45±0.35	0.58±0.07	6.52±0.26	3.33±0.05	5.35±1.0	3.06±0.11	14338.08±2920.2
Phengite Eclogite	50	19.60±2.167	0.59±0.10	1.49±0.26	0.81±0.17	6.91±0.24	3.26±0.08	5.79±1.0	4.77±0.28	2574.07±948.9
Retrograded Eclogite	50	23.83±2.35	0.69±0.21	1.88±0.42	1.09±0.24	6. 6±0.13	3.21±0.10	5.17±0.81	7.4±0.81	455.76± 169.6
Amphibolite	50	40.22±3.15	0.28±0.11	3.65±0.75	1.78±0.22	6.18±0.10	2.91±0.05	5.01±0.35	6.12±0.75	30506.83±32690.5

of their very low content of heavy minerals, since the replacement of garnet by biotite and amphibole during retrogression. They also show very low CNL values because their lack of basic minerals, which are easily altered to hydrous minerals. Their high silica and phyllosilicates content decreases their Vp values (Fig. 3c).

There is a positive correlation between K and Th content calculated in geochemistry and the log tool readings. U and Th distribution is very irregular since they are associated with secondary minerals.

Orthoclase content of orthogneisses is higher than those of paragneisses, so they reflect high GR values, which increases with depth. At lower depths, 1165-1264 m depth, they show high U- and K-contents and lower densities because they are in a fault zone. They are mineralized with concentration of titanomagnetite at 1566-1585 m depth. Othogneisses are homogeneous and massive at lower depths but also interlayered with thin layers of amphibolites (4071-4074, 4028-4032, 4745-4750 and 4955-4960 m depths). This impedance contrasts between the two lithologies may give rise to the strong seismic reflections recognized during seismic survey.

Shearing is more intensive in paragneisses than orthogneisses, leading to their relative lower Vp values and slightly higher CNL values.

Olivine, pyroxene and garnet content of ultramafics increases their density and Pe values, while their lack of acidic felsic minerals decreases their GR values. Serpentinization and chloritization and associated chemically bound water, of those basic minerals raise their CNL values to higher orders of magnitude and decrease Vp values (Fig. 3c). Ultramafics show very low RD values (Fig. 3d) due to low SiO_2, relatively high $FeO+Fe_2O_3$ and high MgO content, which indicate their mantle origin.

Higher CNL and GR (K, Th and U content) and lower RD and DEN values of phengite eclogite (Table 2), is because hydrous and flaky nature of phengites. Their lower densities compared to rutile eclogite are due to that phengite is lighter in density than eclogite. Higher Vp values because phengitic mica remains stable under UHP eclogite facies conditions (Liou *et al*., 2000).

During retrogression secondary hydrous hornblende and plagioclase formed reaction rim or replace omphacite (Zhang *et al*., 1995; Liu *et al*., 2002). So there is a nearly linear decrease in Al_2O_3 and MgO content with an increase in SiO_2 and Na_2O content. This implies that the relatively mobile components were added to the reworked eclogites by ascending fluids during the early stage of exhumation along shear zones (Ji *et al*., 2003) and leads to high readings of CNL and GR (Fig. 4). Titanite also replaces rutile and results in the decrease of DEN and Pe. Grossularite garnet in eclogites, when in contact with ultramafics, has broken down to zoisite epidote and ilmenite and increases CNL and decreases RD values. Those very low RD values are also due to low SiO_2, high $FeO+Fe_2O_3$ and high TiO_2.

Phengite mica can also be altered to biotite and feldspar increasing GR values during retrogression of phengite eclogite.

Eclogites have the highest Vp and density while the retrograded eclogites and amphibolites have successively lower velocities and densities, indicating that retrograde metamorphism can significantly decrease both Vp and density in eclogites (Wang *et al*., 2005). This decrease in Vp during retrogression mainly due to a decrease in garnet content and to an increase in the volume fractions of retrograde materials such as amphibole, mica, zoisite and quartz. Vp also tends to decrease with increasing SiO_2 content. Their variable Vp value is due to anisotropy which is due to the presence of strongly anisotropic retrograde minerals such as amphibole, plagioclase and mica.

Generally variable behavior of different properties of retrograded eclogites (Fig. 5) is due to different rate of

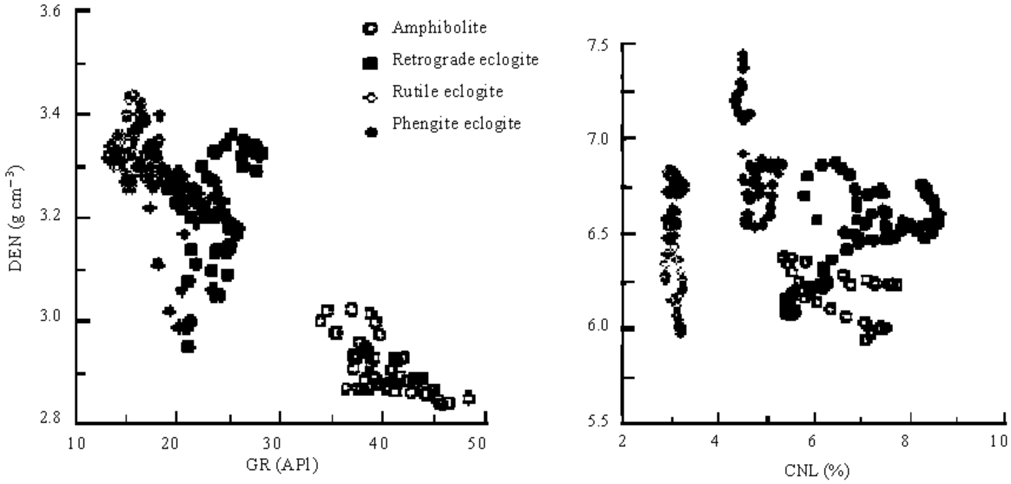

Fig. 4: The effect of retrogression on different physical properties of eclogites

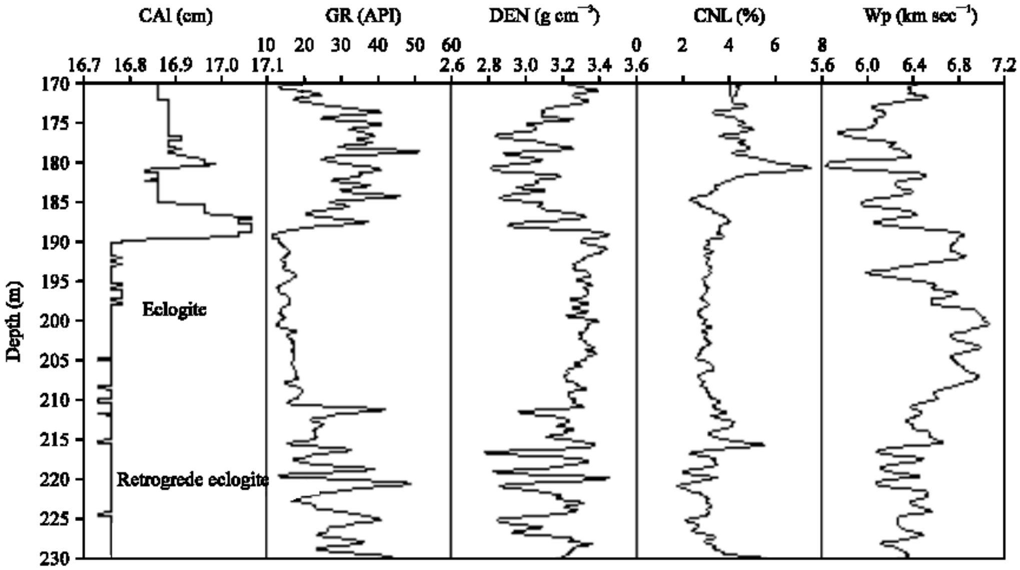

Fig. 5: The boundary between eclogite and retrograded eclogite shown by different well log responses

mineral alteration. This can be compared to nearly constant behavior of eclogites to delineate where retrogression starts. This also proves that amphibolites are the retrograded products of eclogites (Liu *et al.*, 2003).

When Ultramafics are intruded within eclogites, at depth range 608 to 684 m, they have magnetite mineralization in their lower and upper boundaries and this increases their DEN, Pe and Vp and decreases their RD values. When they are in contact with gneisses, at depth range 841-851 m, regional metamorphism enriches their Th-content and hence raises GR values and nearly complete alteration to serpentine indicated by high, constant CNL readings and lower DEN, Pe and Vp values (Fig. 6).

When sheared with eclogites (for example at 1020-1064 m depth) paragneisses mineralized with titanomagnetite. Mineralization in orthogneisses increases U- and K-content while Th-content is nearly constant (Fig. 7a). Both K- and Th- content increase when paragneiss mineralized (Fig. 7b), accompanied by decrease in DEN and Vp.

Generally upon mineralization heavy and basic mineral, $FeO+Fe_2O_3+TiO_2$, content of eclogites and amphibolites increases, while gneisses looses heir minor heavy minerals and gain more felsic minerals, since break

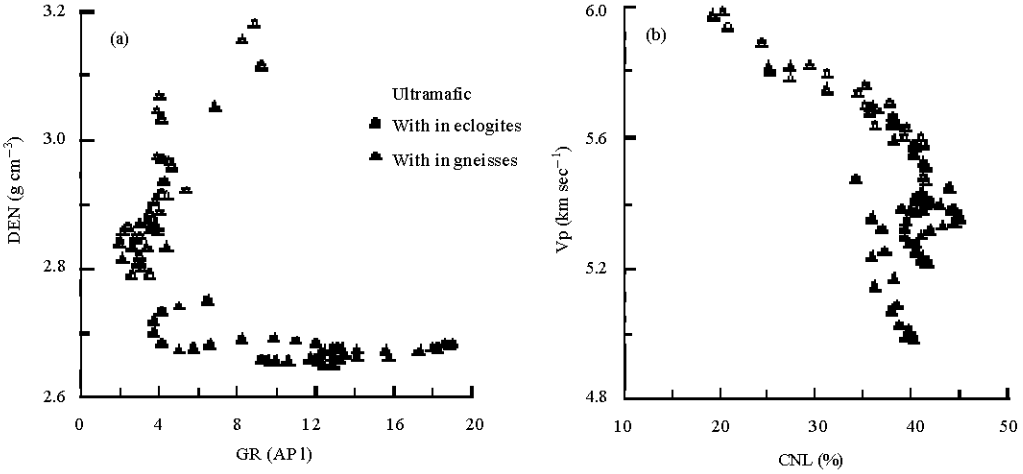

Fig. 6: Ultramafics when in contact with eclogite (mineralized) and with gneisses (non-mineralized)

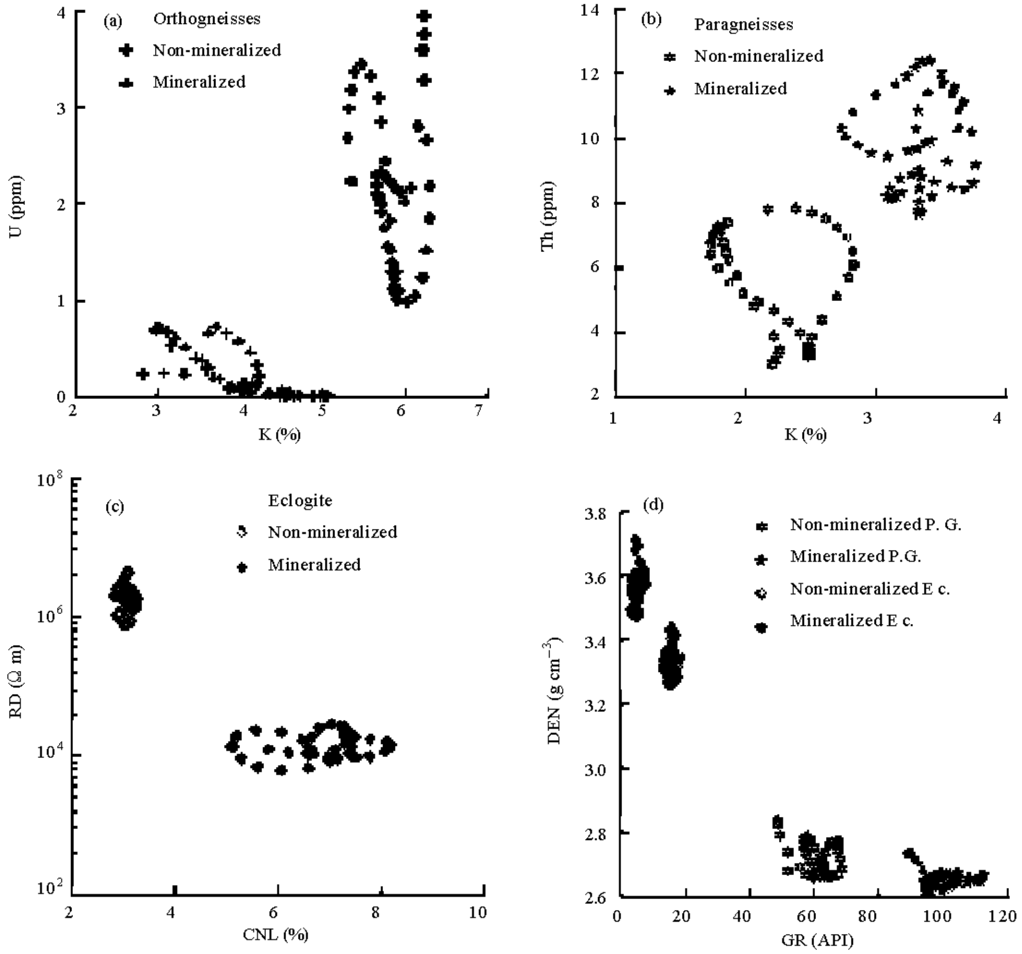

Fig. 7: The effect of mineralization on (a) orthogneisses (b) paragneisses, (c) eclogite and (d) eclogites and paragneisses log responses

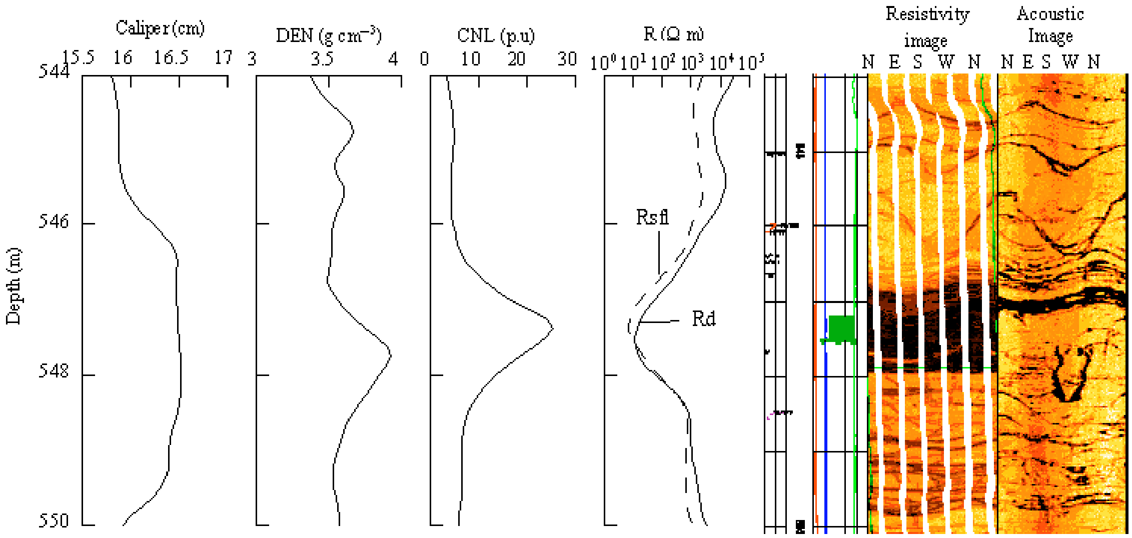

Fig. 8: Different log responses (left) and images (Right) for mineralization in amphibolites

down of grossularite garnet to zoisite epidote and ilmenite and replacement of garnet by biotite and amphibole during retrogression. This increases DEN, Pe and CNL of the former and decreases its GR value and decreases DEN, Pe of the latter and increases its GR readings (Fig. 7c, d and Fig. 8).

CONCLUSIONS

The relationships between DEN, Pe and Vp and heavy mineral and SiO_2 content and between GR and K and Th content give evidence that mineralogy, which is controlled by both chemical composition and metamorphism, is the most significant parameter influencing intrinsic properties of different lithologies and their well log response, in Dabie-Sulu ultrahigh-pressure (UHP) metamorphic belt.

Vp of different rock types of the region is high and their CNL values, except for ultramafics, are low, because subduction to deep levels and accompanied metamorphism under high pressure and moderate to high temperature can leads to compaction and dehydration which are responsible of the former and the latter phenomena respectively.

GR and DEN are the most effective methods to differentiate between different metamorphic rocks of CCSD-MH area. Anisotropism and fracturing and mineralization reduce the usage of Vp and U and RD to differentiate those rocks respectively.

When there is mineralization heavy minerals; including, garnet, rutile, epidote , magnetite and ilmenite; and basic minerals; including olivine and pyroxene; are the main content of eclogites and ultramafics. They are the main factor raising their densities and Pe values. They are accessories in gneisses leading to their low densities and Pe values.

Because phengitic mica remains stable under UHP eclogite facies conditions they show high Vp, Pe, CNL and GR values.

Exhumation of eclogites together with ultramafics is the main reason of retrogression. It decreases DEN and Pe and increases their CNL because the alteration of rutile, grossularite garnet and omphacite into titanite, zoisite epidote and hornblende, respectively. Break down of phengite in eclogites to biotite and feldspar during retrogression increases the radioactivity of the retrograde eclogites and amphibolites, also increases RD of the latter.

This confirms that amphibolites are the retrograded products of eclogites.

Ultramafic's high CNL values are due to alteration of olivine and pyroxene to serpentine during the hydration of peridotites. Regional metamorphism enriches Th-content and hence GR values, of ultramafics when in contact with gneisses.

High feldspar and quartz content of gneisses made them to have distinctive high GR, RD values. The lack of feldspars causes in low GR values of eclogites and ultramafics.

The little content of basic minerals and hence the lack of their secondary alterations decreases the CNL values of gneisses.

Orthogneisses are more radioactive and resistive than paragneisses, because of their higher K-feldspar and quartz content. Shearing lowers Vp and increase CNL readings of paragneisses. Paragneisses sheared with eclogites mineralized with titanomagnetite and those in contact with ultramafics show secondary alteration to serpentinite.

Generally mineralization decreases RD values of different lithologies. Upon mineralization heavy and basic mineral content of eclogites increases, so increase in DEN and Pe, while gneisses lose their minor heavy minerals and gain more felsic minerals, hence their GR values raise.

Although orthogneisses are homogeneous and massive at lower depths but also they are intercalated with thin layers of amphibolites.

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