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Some Structural Features of Sulu Terrane (Eastern China) from Well Logs and Images

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Abstract: The structure of Sulu Ultrahigh-Pressure (UHP) metamorphic belt in eastern China is so complicated and different models have been suggested by many authors. Although, the interpretation of different structural features from geophysical logs is quite ambiguous, but availability of various well logs and images made it possible. At least 2 sets of faults are identified within the studied depth range. One is parallel to the well known Tanlu fault, dipping steeply (69-73°) to ESE (101-105°) direction. They are expected to bring the ultramafics and associate eclogites and paragneisses to upper levels. The 2nd is within the country rocks. They mainly dip moderately to SSE. Those faults are coincidence with shearing and foliation of different metamorphic rocks. CCSD-MH reaches many shear zones at different depths. They mainly dip moderately (42-56°) to southeast (127-149°), coinciding with many shear zones detected in the surface. The eclogite blocks, display strong, flattened foliations and stretching lineations that are generally consistent with those of the country rocks. Locally, the early UHP foliation is crosscut by late amphibolite facies shear zones. Fractures of the upper depth's are steeply dipping to nearly east and west. While, those of the middle and lower depths are mostly of gentle dips to SSE and NNW. The Vp contrast between eclogite and other lithologies is distinctive, so this can locate the high acoustic wave reflectors recognized during seismic survey. No high velocity anomaly at depth between 3.2 and 4.7 km, as expected by seismic survey, is recognized by well logs. The maximum horizontal stress direction is NE-SW as deducted by borehole breakout shown in the acoustic images.

Key words: Geophysical well logging, Chinese Continental Scientific Drilling (CCSD-MH), structural features, Sulu Ultrahigh-Pressure (UHP)

INTRODUCTION

The Sulu-Dabie ultrahigh-pressure (UHP) metamorphic belt in east China is one of the largest known UHP terrane in the world. It marks the deep parts of an EW trending collisional orogenic belt between the Sino-Korean and Yangtze cratons. The Yangtze craton subducted northward and first collided with the Sino-Korean craton at the eastern end during the Late Permian. As the collision proceeded from east to west, the triangular ocean basin between the Sino-Korean and Yangtze cratons closed progressively, causing the Yangtze craton to rotate clockwise about 60° during the Triassic (Zhu *et al*., 1998). After the basin completely disappeared, the 2 cratons continued to converge by continental subduction and shortening during the Jurassic.

The UHP metamorphic rocks of the Dabie-Sulu metamorphic belt have been subducted to at least 100 km depth and experienced UHP metamorphism before being rapidly exhumed from the mantle back to the surface (Liou *et al*., 2000; Liu *et al*., 2002, 2004; Hacker *et al*., 2000).

The belt is commonly considered to be the eastern extension of the Qinling-Dabie orogen, displaced by the Tanlu fault northward approximately 530 km to the Sulu region (Okay *et al*., 1993; Zhang *et al*., 1995a). It is separated from the Sino-Korea craton to the NW by the Yantai-Qingdao-Wulian Fault (YQWF) and the Yangtze craton to the SE by the Jiashan-Xiangshui Fault (JXF).

The major structure of the Donghai County area is characterized by 4 ductile shear zones of complicated shapes, which divide the UHP rocks into 5 UHP rock sheets trending NE and dipping SE. They were active during exhumation of the UHP metamorphic rocks (Yang *et al*., 2005).

Eclogites and ultramafic rocks occur as pods or layers in quartzo-feldspathic gneiss ranging 1-100 mL. Most of the pods are aligned parallel to the regional schistosity of the gneiss and some are folded concordantly with the gneiss.

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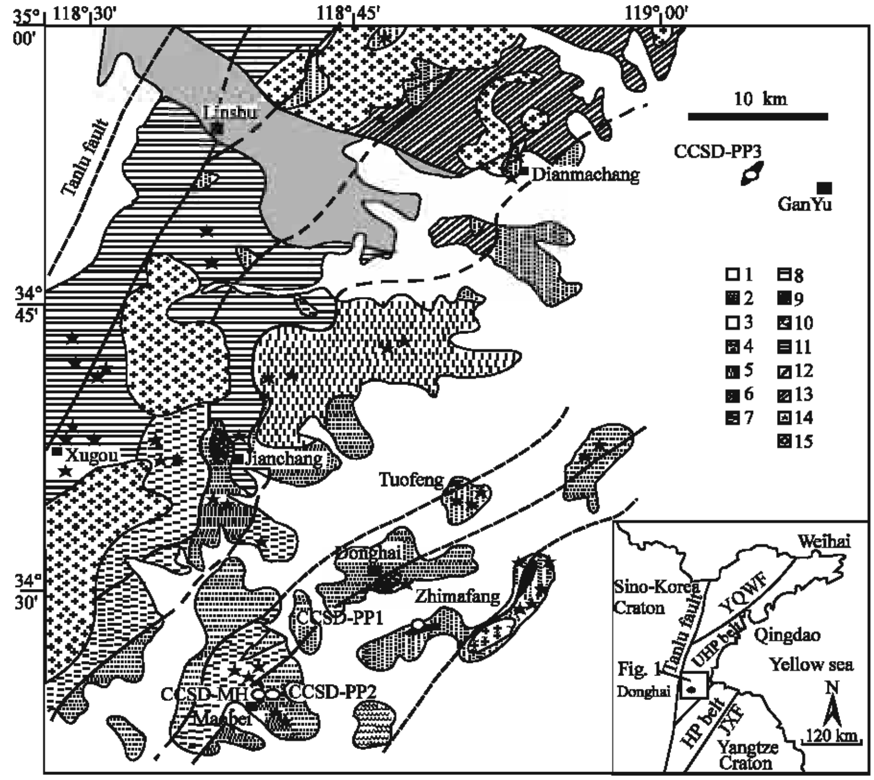

Fig. 1: Simplified geological map and drilling hole locations in the Donghai area, southwestern Sulu terrane (1) Quaternary (2) Tertiary basalt (3) Cretaceous basin (4) Cretaceous granite (5) aegirine-bearing granitic gneiss (6) amphibole-bearing granitic gneiss (7) garnet-bearinggranitic gneiss (8) biotite-bearing granitic gneiss (9) amphibole-bearing and biotite-bearing granitic gneiss (10) epidote-bearing and biotite bearing granitic gneiss (11) supracrustal rocks, including paragneisses, kyanite-bearing and jadeite-bearing quartzite and marble (12) eclogite and ultramafic rocks (13) ductile shear zone or fault (14) coesite-bearing zircon (15) drilling hole. YQWF—Yantai–Qingdao–Wulan fault, JXF—Jiashan–Xiangshui fault

The main hole of the Chinese Continental Scientific Drilling (CCSD-MH) is located in Maobei, the southern part of Donghai County, Jiangsu Province, eastern China Fig. 1. The drilling started in July 2001 and has reached a depth of 5100 m. The aim of the drilling project is to study ultrahigh-pressure metamorphism and related geodynamic processes.

The main purposes of the study are to: locate different structural features at different depths, study the relation between the above structural features and shearing, exhumation and subduction processes, detect causes of strong seismic reflections and the high velocity anomaly at different depths, i.e., to calibrate the seismic reflectors, specially that anomaly between 3.2 and 4.7 km recognized during seismic survey (Kern *et al*., 2002).

MATERIALS AND METHODS

In the last few years the Chinese Continent Scientific Drilling (CCSD) project have been carried out within the UHP belt and different geophysical investigations, including well logging methods, have been performed around this area.

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.

Simultaneous acoustic-Resistivity imaging (STAR II) system of ATLAS' ECLIPS5700, including both Formation Micro-resistivity Imaging (FMI) tool-STAR II 1022XA£©

and Circumferential Borehole Imaging Log (CBIL) tool-CBIL 1671£©, is used in 157 mm diameter borehole drilled using water-base mud. Graphic workstations for fast and interactive image manipulation, processing interpretation of borehole images and their high-resolution color monitors allow recognition of many details. In addition to paper-based interactive dip analyses using rose diagrams, to show azimuth and dip amplitude frequencies.

Data processing also includes statistical calculation of the mean and standard deviation (STD) values of different well log responses.

RESULTS AND DISCUSSION

It can be seen that the area demonstrates complicated structures, containing mainly faults, folds, fractures and ductile shear zones.

Faults: They can be recognized in both resistivity and acoustic images as dark color tone areas. Faults can sharply increase caliper and CNL reading and decrease density, compressional wave velocity and both Rsfl and Rd (Fig. 2).

The fault detected in the depth range 604-606 is steeply dipping (69°) to ESE (105°). It comprises eclogites, which retrograded to amphibolite, in the upper hanging wall and ultramafic rocks in the lower foot wall. This fault leads to the increase of the heavy minerals in the above amphibolites, may be its heat was responsible of metasomatic exchange of elements and their differentiation causing mineralization at this level. It increases density, CNL and Pe values and lowers the resistivity especially in the 576-604 depth range. This leads also for mineralization at depth ranges 547-548 and 555-558 m.

A 2nd fault is found at depth range 706-708 m. It dips steeply (69°) to ESE (101°) (Fig. 3).

It is located with in eclogite which is below this depth is retrograded. This may be one of the abundant eclogites occur as small lenses or blocks less than 20 m in size

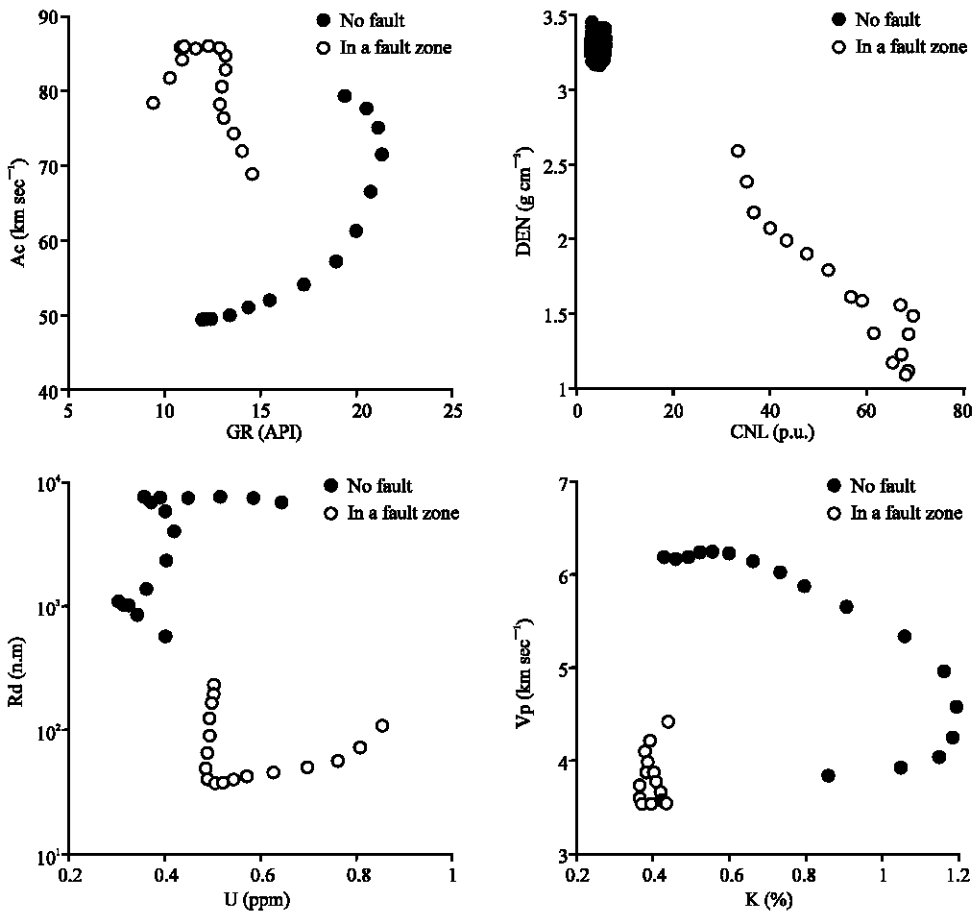

Fig. 2: The effect of fault on different well log responses

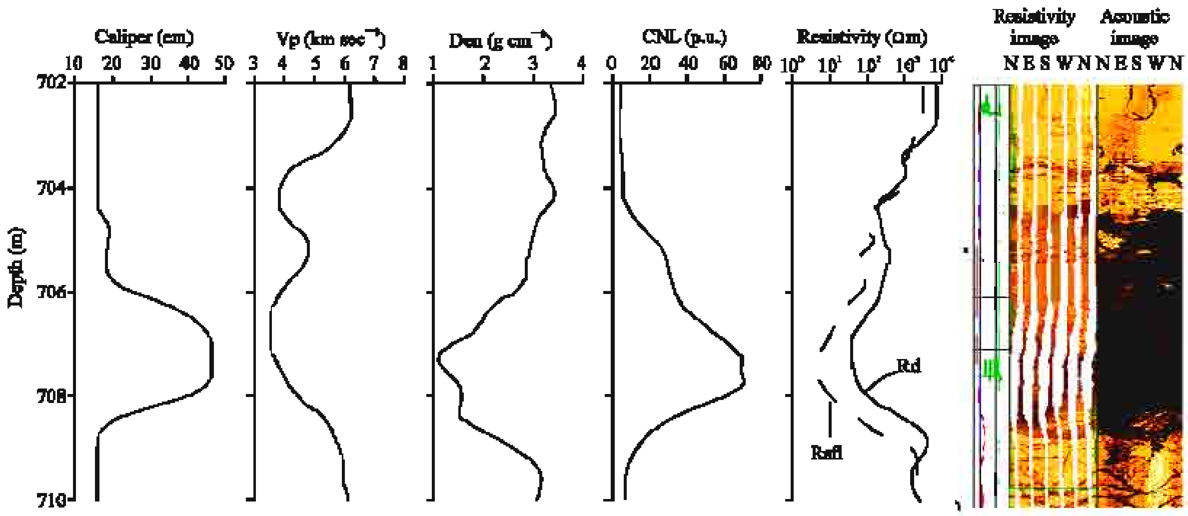

Fig. 3: The fault detected at 706-708 m depth by CCSD main hole logs (left) and images (right)

within serpentinized ultramafics, or as thin layers in gneiss and marble in the Dabie and Sulu regions (Okay *et al.*, 1993).

The third fault related to ultramafics, is at depth range 842-843 m, exactly above a 10 m thick ultramafic body and below a paragneiss unit. It also steeply dips (73°) to ESE (105°).

During post-collision relaxation, the garnet peridotites were expected to be exhumed to a crustal level, followed by exposure on the surface due to doming and erosion of the terrane (Yang *et al.*, 2000). It is probable that those faults are resulted from this doming.

Also surface geology showed that ultramafics may have been derived from the mantle and tectonically emplaced within the continental basement. And they are divided into 2 subunits, possibly by a normal fault.

This set of faults is nearly parallel and looks like the Tanlu fault in the west. It is subvertical to steep east dip (50° to SE). The Tanlu fault apparently displaced the UHP and HP units from the Qinling-Dabie fold belt to the Sulu region and considered as a major cause for the exhumation of the UHP belts as suggested by Okay *et al.* (1993).

There are many faults at lower depths like that at depth range 1157-1162 m. It dips 30-40° to SSE (165°). It is located inside a shear zone. The lower fractures have the same dip angle and direction. Those are parallel and have the same features of those recognized at surface. Also, during seismic survey they found in the upper crust, some strong south-dipping reflectors coincide with surface mylonite zones and the eclogite outcrops of UHPM are also dipping south. Paleomagnetic study suggests that the east side of the Tanlu fault rotated 13-36° counter clockwise relative to the main part of the Yangtze block in the Late Triassic-Late Jurassic and only 4° in the Early cretaceous (Xing *et al.*, 1995). So, if we relocalize clockwise we can get nearly the same direction.

Fractures and foliations: Fracture detection was so certain because several logs confirm their presence. Fractures were either natural, caused by stresses derived from tectonic forces (faults and folds), or induced, caused by drilling stresses or hydraulic pressures. They appear as black sinusoidal traces in both FMS and acoustic images. Caliper straightness deviated in thin zones to larger than bit size matches to fractures. They can be recognized as a sudden drop in shallow SFL resistivity compared to the deep resistivity measurements, sometimes they show uranium peaks. Fractures can be identified by low compressional wave amplitudes in acoustic measurements, a localized decrease in density, or high neuron values at least due to their high content of chemically bound water, which associated with alteration products within those zones.

As shown in Table 1 eclogites, amphibolite and paragneisses are characterized by a finely and regularly spaced fractures. They highly dip (56-58°) to ESE (96-114°). Ultramafics have the same set of fractures but with less dip angle (45°). This set is also found in eclogites at lower depths, for example 4955-4960 m, but moderately spaced and moderately dipping (44°) to nearly east (80°). They have the same dip and strike characteristics of the Tanlu and related faults.

Eclogites and gneisses have a distinctive finely spaced foliation (Salim *et al.*, 2007). They dip gently to moderately (37-43°) to SSE (140-166°) Fig. 4. This set is

Table 1: Fractures dip angle and direction in different lithologies of the studied borehole

Lithology	Depth range (m)	Number of fractures	Dip angle±STD (Degree)	Dip direction±STD (Degree)
Eclogites	428-451	8	61.3±5.7	45.4±15.9
		37	57.9±11.2	109.5±12.3
		12	32.0±11.7	271.9±15.4
	1064-1082	22	42.5±18.9	140.0±13.8
Amphibolite	576-604	20	64.9±7.1	58.1±12.6
		33	58.2±14.7	96.3±9.6
		6	34.3±20	217.3±12.5
Orth. Gneisses	1200-1220	64	36.9±5.5	166.2±5.2
	4960-4980	26	47.2±5.3	333.8±7.9
Para. Gneisses	853-880	43	56.1±10.2	114.6±11.3
		10	52.4±9.9	276.8±14.1
	1045-1065	26	38.1±10.1	141.7±17.1
Ultramafics	608-644	40	44.8±13.8	97.6±9.0
		13	40.4±21.2	316.5±21.7
		14	22.6±7.5	52.1±19.3
		8	62.1±12.4	193.6±11

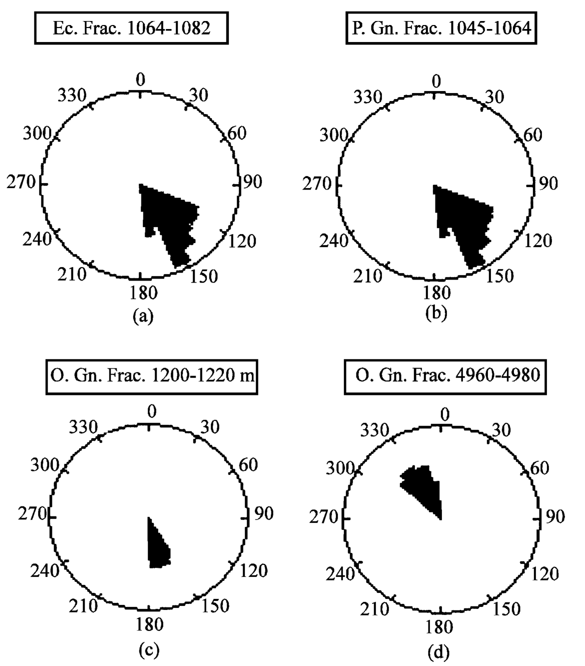

Fig. 4: Rose diagrams showing NW-SE dipping of fractures in eclogites (Ec.) and gneisses (P. or O. Gn.), Frac. is an abbreviation for fracture

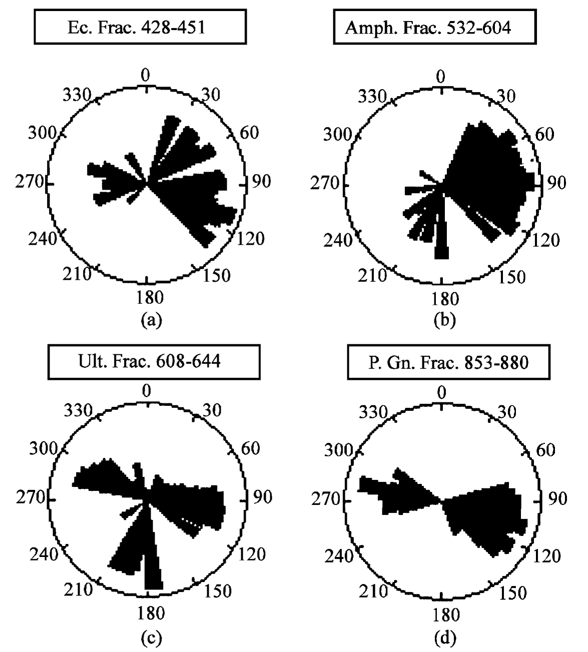

Fig. 5: Rose diagrams showing different fracture sets for different lithologies detected in CCSD-MH, Ec., Amph., Ult., P.Gn. are abbreviations for Eclogite, Amphibolite, ultramafic and Paragneisses, respectively

parallel to the overlying fault and shear zones that mentioned in the above text. Also consistent with that Gneisses trend NE and dip 20-50° SE in outcrops of the area.

This set is steeply dipping (70-86°) to SSW (190-230°) in the gneisses of lower depths.

Bellow 1164 m depth gneisses, especially orthogneisses, are highly fractured, foliated, may be faulted and show relatively high U-content. Bellow the depth 4385 the intensity of fracturing is low. Gneisses at lower depths show foliation, which moderately to highly dip (45-79°) to NW and NNW (300-354°).

The above is in consistent with that, in UHP unit the main foliation dip south (150-170°/40-50°) and lineation plunges south (130-160°/25-30°). That indicates a north-west overthrusting and northwest-southeast extension (Hacker and Wang, 1995)

Eclogites and amphiolites show another set of fractures dipping highly (61-65°) to NE (45-58°) (Fig. 5a, b). This set is of gentle dip (23°) in ultramafics.

Eclogites, amphiolites and paragneisses also characterized by fractures, which are widely spaced and moderately dipping (32-52°) to SW and W (217-277°). Ultramafics also have the same kind of fracturing, but dips to NW (317°) (Fig. 5c).

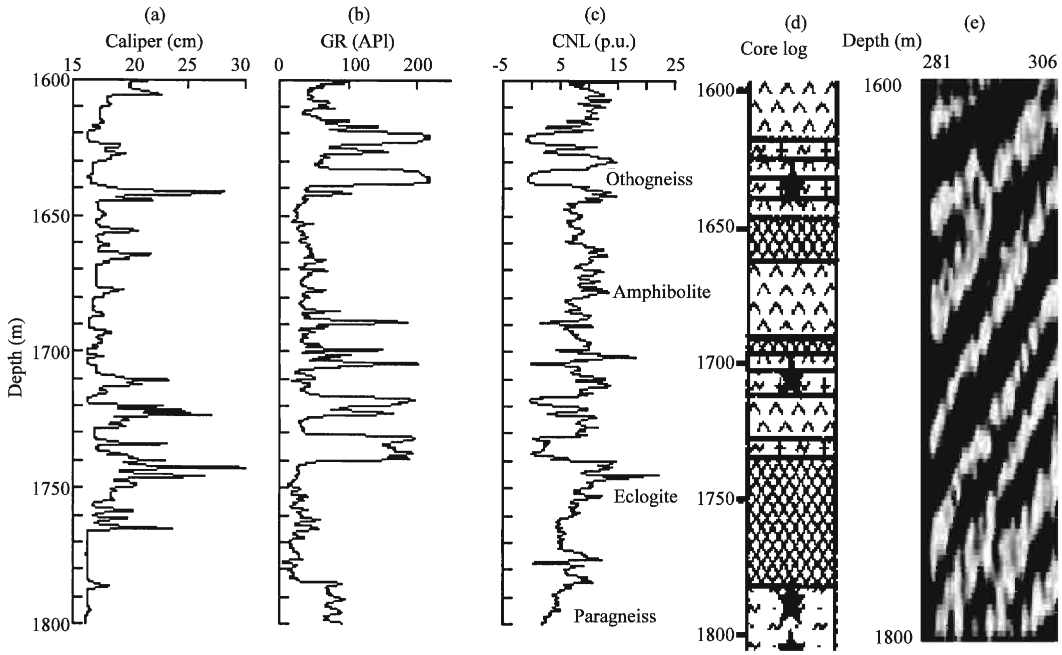

Fig. 6: The well-logging results showing shearing at a depth of 1600-1800 m of the CCSD main hole (a) Caliper (b) Gamma Ray (c) Compensated Neutron Log curves (d) Core Log and (e) seismic reflection profile (Zhao *et al*., 2004)

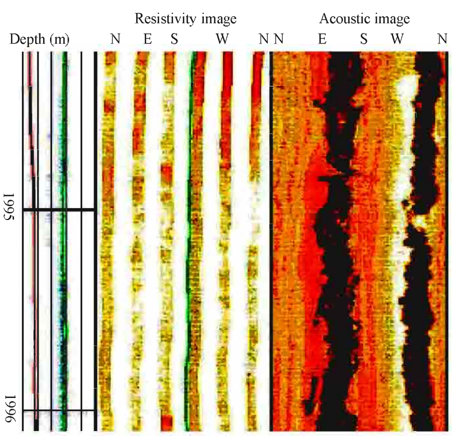

Fig. 7: The minimum horizontal stress direction shown on acoustic images

Generally from Fig. 4 and 5, it is recognizable that the upper depth's fractures are steeply dipping to nearly east and west. While, fractures of middle and lower depths are mostly of gentle dips to SSE and NNW.

Shear zones: In the earth's crust, large-scale ductile shear zones are characterized by mylonite, lineation and foliation parallel to the orogenic trend and mineral stretching features. Shear zones resulted from mass displacement caused by compressional forces perpendicular to the orogenic belt. They usually formed in the middle crust and exhumed to the upper crust in the post-orogenic stage. During the shearing process, brittle deformation and inelastic creep coexisted. The ductile shear zones consist mainly of gneisses and inserted eclogites produced by side-displacement of shearing process. The thickness of the eclogites is about 10-25 m, sandwiched between gneisses, forming the ductile shear rock-suite. The thickness of the suite can reach about 200-450 m.

Shearing always increases Cal, U, CNL values and decreases DEN and VP readings. Shearing is more intensive in paragneisses than orthogneisses, leading to their relative lower Vp values and slightly higher CNL values. Chinese Continent Scientific Drilling Main Hole reaches many shear zones, for example those at depth ranges 850-1300, 1600-1800 m (Fig. 6) and 4000-4290 m, as the sheets are dipping moderately (42-56°) southeast (127-149°). Those Coincide with many shear zones in the area trending NE and dipping SE also with the stretching lineation which plunges to SE direction.

Boundaries: Sharp contacts between all lithologies of the area can be recognized by different well logs. High GR (60-247 API) and DEN (3-3.5 g cm^{-3}) values can differentiate between gneisses and eclogites, respectively. Even the approximate boundary where retrogression stars can be delineated from well logs (Salim *et al*., 2008). High CNL values (27-44 p.u.) can locate a distinctive boundary between ultramafics and the adjacent rock units.

Seismic reflections: General high Vp values, 7.0-8.0 km sec^{-1}, of eclogites is due to their source area, the mantle (Yang *et al.*, 2005), but those values decreased with exhumation and accompanied retrogression, shearing and serpentinization. There is general downward increasing of velocity probably due to closure of fractures.

The large compressional velocity anomaly consistently occurs at the gently dipping contacts between eclogites, or amphibolites and other rocks such as paragneiss and orthogneiss or ultramafics. While, a moderate anomaly is between paragneisses and orthogneisses or between gneisses and ultramafics. This is in consistent with the strong and the moderate seismic reflections appear at contacts and shear zones during seismic survey, respectively (Ji *et al.*, 1997a).

Because velocity of serpentine in ultramafics can decrease to 6.0-6.7 km sec^{-1}, density also reduces obviously; so its boundary with eclogites can also be a reflection interface.

No high velocity anomaly at depth between 3.2 and 4.7 km recognized by well logs. This depth range is mainly gneisses showing Vp values <6.0 km sec^{-1} less than expected 6.8 km sec^{-1} during seismic survey (Kern *et al.*, 2002). This depth range is characterized by high fracturing. Seismic reflections between eclogites (amphibolites) and gneisses can be expected for example at depth ranges 3015-3035, 3048-3058, 3235-3245, 3298-3305, 4070-4074, 4127-4132, 4745-4750, 4862-4864 and 4955-4960 m.

Borehole breakout: This occurs in the minimum horizontal stress direction where shear failure takes place. It is perpendicular to the maximum horizontal stress direction which causes tensile cracks.

In the study area the direction of the low reflection zones, appear as 2 parallel dark strips, is NW-SE Fig. 7. This proves that the maximum horizontal stress direction is NE-SW. This may be due to the general north word direction of the subduction of Yangtze craton and its rotation clockwise about 60° during the Triassic.

CONCLUSION

Tanlu fault with NNE trend is one of the main controlling factors for structural events in the studied area since, Triassic. Several local faults oriented subparallel to Tanlu fault is recognized at different depths. Three faults at depths 604, 706 and 842 are bounding ultramafics. They are with general NNE trend and dipping steeply (69-73°) to ESE (101-105°) direction. They are expected to bring the ultramafics and associate eclogites and paragneisses to those levels. There are many faults at lower depths within country rocks. They mainly dip moderately to SSE. Those faults are coincidence with shearing and foliation of different metamorphic rocks.

Fracturing of eclogites, ultramafics and paragneisses, especially at shallow depths, is of general steep dipping to nearly east. It is related to the Tanlu and subparallel faults.

Foliations of most eclogite bodies are subparallel with that of country rocks, gneisses, dipping moderately to SSE, suggesting *in situ* ultrahigh pressure metamorphism for eclogites and gneisses. All the pre-Cretaceous units are inferred to have formed during the same single continental collision (Ernst *et al.*, 1997) and all contain a south-dipping foliation, contrary to what one might expect from formation in a north-dipping subduction zone.

NNW-SSE dipping fractures in gneisses can be related to the subduction of Yangtze plate. This is in consistent with the results of seismic survey which showed many dipping events in the upper crust, indicating the UHPM belt is dipping northward. In the upper crust, some strong south-dipping reflectors coincide with surface mylonite zones and the eclogite outcrops are also dipping south.

The UHP rock units exhibit penetrative, S-to SE-dipping, ductile deformation structures. Many shear zones are detected at different depths, for example those at depth ranges 850-1300, 1600-1800 and 4000-4290 m.

Boundaries between different lithologies can be identified due to the large difference in well log response of most rock units.

The acoustic impedance contrast between eclogite and other lithologies gave rise to the strong and moderate seismic reflections recognized during the seismic survey.

No high velocity anomaly at depth interval 3.2-4.7 km recognized by well logs, as expected during former seismic survey. This depth range is characterized by high fracturing and one of the shear zones.

The maximum horizontal stress direction in the area is NE-SW, detected from the bore hole breakout images.

At least 3 stages of deformation can be recognized. The first stage of deformation was represented by parallel foliation, dipping NW, formed under conditions of eclogite facies of metamorphism during subduction of Yangtze plate. The 2nd stage of deformation was represented by parallel lineation with NW-SE fold hinges produced during early exhumation and the third stage was brittle ductile deformation, shearing, during late exhumation and it is associating with Tanlu fault set.

The interpretation of different structural features, their location, orientation and width from geophysical logs is still quite ambiguous in spite of much study on the subject.

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