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All Authors	Myo Min, Khin Khin Lin, Qinglai Feng, Chongpan Chonglakmani, Dieter Meischner, Rucha Ingavat-Helmcke, Dietrich Helmcke
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Tracing Disrupted Outer Margin of Paleoeurasian Continent through Union of Myanmar*

Myo Min Khin Khin Lin

Department of Geology, University of Mandalay, Mandalay, Myanmar

Feng Qinglai

Faculty of Earth Sciences, China University of Geosciences, Wuhan 430074

Chongpan Chonglakmani

School of Geotechnology, Suranaree University of Technology, Nakhon Ratchasima, Thailand

Dieter Meischner

*Goettingen Center of Geosciences, University of Goettingen, Goldschmidtstr 3,
D-37077 Goettingen, Germany*

Ingavat-Helmcke Rucha

*c/o Goettingen Center of Geosciences, University of Goettingen, Goldschmidtstr 3,
D-37077 Goettingen, Germany*

Helmcke Dietrich

*Goettingen Center of Geosciences, University of Goettingen, Goldschmidtstr 3,
D-37077 Goettingen, Germany*

ABSTRACT

Based on stratigraphy, facies distribution and paleontology of upper Paleozoic and Triassic strata in Malaysia, Thailand, Myanmar and Yunnan (China), the location of the division between the outer margin of the disrupted Paleoeurasian continent and possible Gondwana-derived terranes is discussed. It is proposed that this division is located much further to the west than that has usually been maintained.

KEY WORDS Southwest Asia, Paleotethys, tectonic, boundary between Gondwana and Paleoeurasian continents.

INTRODUCTION

During the past two decades, a majority of geoscientists have regarded mainland Southeast Asia as composed of Gondwana-derived terranes which crossed "Paleotethys" to collide with the former Paleoeurasian continent in Late Triassic/Jurassic (Metcalfe, 1999; Scotese and Golonka, 1992; Sengör, 1979). The main branch of "Paleotethys" was believed to be situated either to the south of the Red River in northern Vietnam, or along the Nan-Uttaradit-Sa Kaeo-Bentong-Raub line in Thailand and Malaysia.

Many facts concerning the stratigraphy, the distribution

of facies and the paleontology of northern Thailand, western Yunnan and the eastern parts of the Union of Myanmar were more or less ignored in these publications. This situation provoked criticism, and Helmcke (1985) proposed that the outer margin of the Paleoeurasian continent extended much further west, and included large parts of the Union of Myanmar. At that time, no conclusive evidence was known to us to define a possible terrane boundary between the regions in northern Thailand and eastern Myanmar which are composed of northern continental crust and those areas of mainland Southeast Asia which are characterized by the sediments of the Phuket Group and its equivalents (Singha Formation, Lebyin Formation, Mergui Group, Kongshuhe Formation).

Based on data from the region of Mae Sariang in northwestern Thailand, a possible terrane boundary between the margin of the Paleoeurasian continent and Gondwana-related terranes has been localized more precisely (Caridroit et al.,

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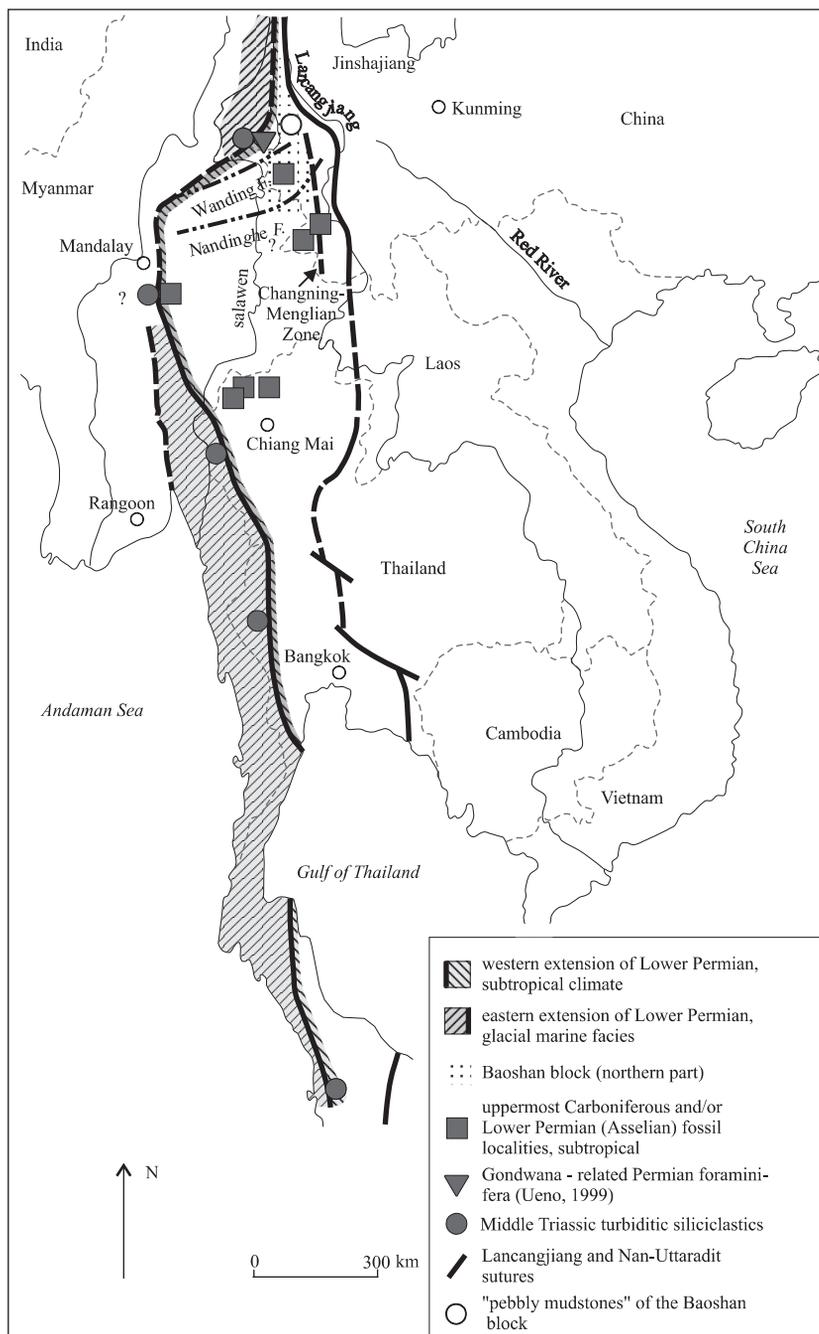


Figure 1. Proposed location of disrupted outer margin of Paleoeurasian continent.

1993; Helmcke et al., 1993; Töfke et al., 1993). However, in many areas of the Shan States of the Union of Myanmar, which are difficult to access, it is still quite problematic to trace this boundary. However, it is necessary to connect the known segments of this division in Malaysia and Thailand with its proposed position in western Yunnan.

In this contribution, we try to trace the outer margin of Paleoeurasia through the Union of Myanmar on the basis of previously published data (Fig. 1). However, a short evaluation of some paleogeographic terms appears necessary before the main arguments for the proposed location of the boundary are discussed.

CRITERIA FOR A CONTINENT/TERRANE BOUNDARY

The best arguments (Table 1), which can be used to trace this boundary, are based on the assumption that the different continents and surrounding continental shelves, which are today integrated into mainland Southeast Asia, were, during the Late Paleozoic, situated in quite different climatic zones. This is especially true for the uppermost Carboniferous and the lowermost Permian when the Permo-Carboniferous glaciation peaked in eastern Gondwana, while on the Yangtze platform, for example, tropical to sub-tropical conditions prevailed. Therefore, special reference will be made to climatic sensitive sediments and faunas of this period. This approach follows quite

strictly the original definition of “Gondwanaland” and “Angaraland” as introduced by Suess (1909, 1901, 1888, 1885, 1883), for this definition refers to the distribution of floras of Late Paleozoic, especially the Glossopteris-flora of “Gondwanaland”.

In modern literature, however, the term “Gondwana” is often used to describe a super-continent configuration amalgamated during the “pan-African” orogenic event at approximately 0.55 Ga (Unrug, 1997), i. e. this term is used to describe a possible configuration of the continents at a time more than twice as long as the original definition requires. According to our conviction, however, this approach raises many problems. With respect to the region treated in this contribution: whether “pan-African” ages could be proved that it would help to trace the boundary or not (Zhong, 2000; Ren et al., 1999).

There remains a major problem: The original definition of the term “Tethys” (Suess, 1901) refers to the nature of the marine fauna of Mesozoic, and hence to a period different from the definitions of “Gondwanaland” and “Angaraland” (the continents bordering Tethys to the north and south). Therefore, since this term refers to a different period, it is questionable

whether it can be applied correctly in this discussion. However, the first plate-tectonic reconstructions of the Late Paleozoic “Pangea”—configuration of the earth show the triangle-shaped ocean between eastern Gondwana and the former northern continents (Wilson, 1963), to which the term Tethys has been applied.

As discussed in many recent papers (Zhong, 2000; Yin et al., 1999; Liu et al., 1991), there still remains the possibility that this oceanic realm was an “Archipelagic ocean”, i. e. an oceanic realm in which many smaller continental blocks were distributed at different latitudes, and separated from each other by oceanic crust. Such a model would also explain the strong facies variations between sedimentary sequences of the same age. The Indonesian archipelago may serve as a modern analogue. Therefore, observations which prove that an oceanic realm was still present during Middle Permian to Middle Triassic, between the Gondwana-related terranes and the non-Gondwana northern continental regions, are as equally important as the presence of sediments indicative of different climatic conditions on the respective continents and continental shelves.

TABLE 1 SIGNIFICANT FEATURES USED FOR DIVISION OF MAIN ELEMENTS OF SEASIA WITH EMPHASIS ON CARBONIFEROUS TO TRIASSIC (BASED ON WANG ET AL. (1997))

	Gondwana and Gondwana-derived terranes	Tethys (Paleotethys)	Northern continents and related terranes
Triassic	U		granites closure of Triassic rifts
	M	synorogenic clastics (flysch)	
	L	pelagic sediments	Upper Permian - Triassic rifting
Permian	U		<i>Paleofusulina</i> Emeishan basalt <i>Verbeekina</i> Middle Permian synorogenic clastics (flysch)
	M	(oolithic limestone) first limestone	connection with arctic fauna realm (<i>Pseudoschwagerina</i>), limestones with massive corals and oolitic limestones
	L	glacial marine sediments no fusulinids	Jambi Flora of Sumatra
Carboniferous	<i>Glossopteris</i> flora		? <i>Walchia</i> <i>Paripteris</i> flora
pre-Carboniferous	granites with pan-African ages		

Detailed paleomagnetic investigations may provide a key to solve these problems. However, rocks from mainland Southeast Asia formed in Permian and Triassic, during this geodynamically crucial period, are most likely to have been affected by thermal overprinting during later periods. The results pub-

lished by Richter et al. (1999) for Peninsular Malaysia and Langkawi Islands are not encouraging, nor are the conodont colour alteration data recently published by Metcalfe (2000). Similar problems are to be expected in northern Thailand and western Yunnan. Paleomagnetic data are therefore not consid-

ered in this paper.

For northern Thailand, Toriyama (1944), Konishi (1953) and Baum et al. (1970) have published convincing arguments, which exclude the possibility that the regions to the east of Mae Hong Son can be rightly regarded as “Gondwana”-related (Ueno and Igo, 1997; Fontaine et al., 1993), therefore, the suggestion for a possible position for “Paleotethys” along the Nan-Uttaradit line was, from the beginning, highly problematic (Helmcke and Lindenberg, 1983).

A more realistic solution was published by Cooper et al. (1989). They show a small sliver (Phuket Terrane) in Peninsular Thailand and in Myanmar as a separate terrane and interpret only this sliver as “Gondwana”-related. Brinckmann (Bender et al., 1983) and Mitchell (1992) also discussed a division of these regions from the regions further east. According to Mitchell (1992) and Brookfield (1996), the pebbly mudstone or diamictite unit (Phuket Group and equivalents) represents a distinct terrane.

LOCATION OF BOUNDARY SOUTH OF MYANMAR

In northern Malaysia, we locate the continent/terrane boundary to the west of the granites of the Main Range of Peninsular Malaysia, thus leaving only the Langkawi Islands and a narrow stretch of the Peninsula in the “Gondwana” realm. The main reasons for this decision are the nature of the Semangkol Formation and the age and nature of the granites of the Main Range and Penang Island.

The Semangkol Formation is described as an assemblage of Permian to Middle Triassic ribbon cherts and Middle Triassic siliciclastics, deposited by turbidity currents (Sashida et al., 1995; Spiller and Metcalfe, 1995). Therefore, this formation appears to be similar to the Triassic sequence known from Mae Sariang (northern Thailand) and an indicator of a former oceanic realm to the east of the Langkawi Islands, which host the Singha Formation (Stauffer, 1983). The granites of the Main Range of Peninsular Malaysia are mainly S-type and Triassic. This is, in contrast to the younger, mainly Cretaceous granites known, for example, from Phuket Island.

From northwestern Malaysia through Peninsular Thailand into northwestern Thailand, the exact location of the demarcation line is still little supported. However, the distribution pattern of the granites may help, as well as the distribution of sediments similar to the strata of the Phuket Group and associated Permian limestones, as described by Fontaine et al. (1994). These sequences are characterized by the lack of Lower Permian carbonates and low diversity faunas in the younger limestones (but with Shanita). There still remain some problems with the outcrops of “pebbly mudstones” near Surat Thani on the Peninsula (Lumjuan, 1993), and the interpretation of the granites in the region (Cobbing et al., 1992); according to our observations, however, these pebbly mudstones are lithologically similar to sediments typical of the Phuket Group.

A locality with Triassic siliciclastics, possibly deposited as turbidites was mentioned by Bunopas (1981) from localities along the river Khwae Yai some 40 km west of Kanchanaburi.

Along the highway from Tak-Mae Sot in western Thailand, an outcrop of pelagic limestones of Triassic is known from 50 km (Fontaine and Suteethorn, 1988).

Probably the best outcrops of pelagic sediments, west of the margin of the former northern continent, can be studied in the surroundings of Mae Sariang in northwestern Thailand. Here, a Triassic sedimentary sequence of typical pre-orogenic and syn-orogenic strata is exposed, consisting of true ribbon cherts with abundant radiolaria, pelagic limestones with radiolaria and thin-shelled pelagic bivalves, overlain by a thick siliciclastic turbidite sequence. This flysch-type sequence contains *Posidonia*, *Halobia* and ammonites in the intercalated shales and is of Middle to Late Triassic (Töfke et al., 1993). In these strata, coarse siliciclastics derived from a high-grade metamorphic terrain which was probably situated to the east of Mae Sariang.

Continental red beds, which crop out west of Mae Sariang were formerly mapped as Lower-Middle Triassic strata, unconformably overlying Paleozoic sediments, and believed to form the basal layers of the above-mentioned pelagic sediments (Baum et al., 1981). Recent mapping and paleontological data, however, proved that these strata are younger (probably Jurassic). This conclusion derives from radiolarians of Permian and Triassic found in pebbles contained in these clastics (Cardroit et al., 1993). Based on this new evidence, the continental beds are interpreted as a post-orogenic overlap sequence. The regions east and west of Mae Sariang may have been on different plates or terranes prior to the Middle Triassic.

Tectonic units to the east of Mae Sariang are not Gondwana-derived terranes. This can be demonstrated in the region between Mae Hong Son and Pai in northern Thailand (Baum et al., 1970; Konishi, 1953; Toriyama, 1944). This region was restudied by Fontaine et al. (1993) who showed that shallow marine limestones were being deposited during most of the Carboniferous and Permian. These limestones show abundant indications of warm climatic conditions (lowermost Permian, for example; *Pseudoschwagerina* and compound corals). They were deposited on a stable platform which formed near the margin of the disrupted continent. Also the thick piles of mature arenites, deposited during parts of the Carboniferous (Fujikawa and Ishibashi, 2000) in this region, substantiate this interpretation.

LOCATION OF BOUNDARY IN MYANMAR

Pebble mudstones from a narrow belt along the western edge of the Shan plateau are known as the Lebyin Formation and equivalents (Mitchell, 1992). According to available data and descriptions, the Lebyin Formation, as developed south of Mandalay (Maung, 1985, Fig. 15, Fig. 18), can rightly be compared with the strata of the Phuket Group in Peninsular Thailand or the Kongshuhe Group of the Tengchong block in western Yunnan. But such sediments are missing in Myanmar further to the east, where carbonates dominate.

The description by Garson et al. (1976) of the areas around Neyaungga and Yengnan, Southern Shan States, is of

special interest for the more precise location of the discussed boundary. Garson et al. (1976) mentioned a narrow belt composed of sediments, probably of Late Triassic (Ma-u-bin Formation), which stretches along the Pan Laung fault. This strip of probable Upper Triassic sediments may extend south to Kalaw and beyond (Garson et al., 1976, Fig. 4). The Ma-u-bin Formation does not occur anywhere else in this area. Garson et al. (1976) suggested that these strata are turbidites, which would be comparable to the Triassic siliciclastics in the area of Mae Sariang (Thailand) between Luxi and Ruili in western Yunnan. The age of the Ma-u-bin Formation is unfortunately not based on faunal evidence but only indirectly indicated by a good Rhaetian flora in coal seams intercalated in the overlying Loi-an Series. According to Mitchell (1992), the strongly deformed strata of the Ma-u-bin Formation are overlain unconformably by red beds of probably mid-Jurassic.

In east of the Pan Laung fault and the Triassic sediments, the Permian is characterized by a thick pile of carbonates (Thitsipin Limestone Formation) deposited under warm climatic conditions, as indicated by the occurrence of corals and typical fusulines. Garson et al. (1976) and Amos (1975) also described limestones of lowermost Permian age with *Pseudoschwagerina* from the Thitsipin Limestone Formation (Garson et al., 1976, Table 1, Table 2), thus confirming that the situation in the Southern Shan States is comparable to the situation in northern Thailand. However, most fossil-localities in the Thitsipin Limestone Formation are of upper Lower to Middle Permian age (including such characteristic fusulines as *Verbeekina*).

If the series near Mae Sariang are related to the Triassic strata described by Garson et al. (1976) along the Pan Laung fault, then the strip of glaciomarine sediments (Lebyin Formation and equivalents) continuously reduces in width to the north between the Pan Laung fault and the Shan Scarp until it reaches the region of Mandalay.

At present, it is still problematic to continue this boundary from the region of Mandalay further into western Yunnan, for the geology of the Northern Shan States is still little known. It is clear, however, that the boundary must turn sharply and rapidly away from Mandalay towards the northeast or east to enter western Yunnan. This sudden turn may be caused, or influenced by a strong younger (Himalayan) overprint.

LOCATION OF BOUNDARY IN WESTERN YUNNAN

In Yunnan, the trace of the "Paleotethys (mainbranch)" has been sought during the past decades along various "sutures". In recent years, however, most Chinese specialists (including Feng Q) decided to place this division along the "Changning-Menglian belt", east of the Baoshan block (Zhong, 2000; Fang et al., 1996). Some other authors (including Helmcke D and Ingavat-Helmcke R), however, favoured a position further west, i. e. possibly west of the Baoshan block along the Nujiang zone.

For both suggestions, good arguments are at hand and a

final decision should be left open for the present. The main points of the controversy are the interpretation of the diamictites of the Dingjiazhai Formation on the Baoshan block and the occurrence of Lower Permian fusulines in this region. While the diamictites of the Kongshuhe Formation on the Tengchong block are very similar to those of the Phuket Group in Peninsular Thailand, those of the Dingjiazhai Formation on the Baoshan block differ strongly: They contain mainly pebbles of oolitic limestones, which are possibly derived from the local Carboniferous Pumenqian Formation (Heinemeyer, 1996; Jin, 1994). The distribution pattern of the Lower Permian fusulines is controversial, for *Pseudoschwagerina* (a typical Tethyan element) was found near Zhengkang on the southern Baoshan block (Wang et al., 1997), while Ueno (1999) reported Gondwana-related foraminifera (*Eopolydiexodina*, *Shanita*) from an area evidently also near Zhengkang. Apparently more detailed research is needed, and future cooperation between geologists from China and Myanmar in this matter is highly desirable.

From Landsat-image interpretation, a direct connection between the southernmost outcrops of the Changning-Menglian belt in China, and the region of the Pan Laung fault, south of Mandalay in the Union of Myanmar (as well as a direct connection with the region of Mae Sariang, Thailand), seems to some of us (Helmcke D) quite unlikely. This, however, is a weak argument, as long as it is not supported by extensive fieldwork. A direct connection between the Changning-Menglian belt and the outcrops along the Nan-Uttaradit zone, or with a "cryptic suture" in the region of Chiang Rai or Chiang Mai (as discussed in some papers) would only be possible, if this "suture" could be traced across the belt characterized by high-grade metamorphics associated with huge granite intrusions, which stretches from the Doi Inthanon region of Northern Thailand, via the eastern parts of the Union of Myanmar, to the Lincang region of southern Yunnan. Furthermore, the sections with the typical warm water sediments of Carboniferous and Permian, known between Mae Hong Son and Pai in northwestern Thailand, are in contradiction to this suggestion.

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Identification and Correction for MT Static Shift Using TEM Inversion Technique^{*}

Yang Changfu

Department of Earth Science, Nanjing University, Nanjing 210093

Lin Changyou

Lanzhou Institute of Seismology, China Seismological Bureau, Lanzhou 730000

ABSTRACT

The inversion of TEM data, using the observed magnetic fields instead of that of apparent resistivities data in this paper, avoids the errors caused by the definition of the apparent resistivity. The inverted results by fitting the magnetic fields of the transmitter source's image with the observed magnetic fields are relatively less affected by the conductivity inhomogeneity. The MT apparent curve is calculated on the basis of the conductivity model constructed from the TEM inversion results. This curve is used as a reference curve for the correction of MT static shift, which makes the correction more reliable. Meanwhile, the domain transformation is also achieved from time to frequency between the two kinds of electromagnetic data. Therefore, the correction of the MT static shift is actualized using TEM inversion method. The corresponding application research shows that this method is very effective for the identification and correction of the MT static shift.

KEY WORDS TEM, inversion, MT, correction of static shift.

INTRODUCTION

The field and theoretical studies show that in the presence of near-surface inhomogeneities, MT apparent resistivity curves on the log apparent-resistivity versus log frequency display are always shifted in line with a factor, constant in all frequencies, with the impedance phase being unaffected, or with the static shift (Jones, 1988).

It should be noted (Sternberg, 1988) that the parallel shift between two MT curves (TE and TM) at an MT site indicates these static shift effects. However, the absence of a displacement between these curves does not guarantee that there are static shifts. In general, the true resistivity may lie above, below, or between the curves from the two polarizations, or may agree with any one of the two polarization curves. The shifts are related to the boundaries of a surficial conductive inhomogeneity, to the direction of the boundary and to the distance between the boundary and the MT site. The TM mode is more sensitive to surficial charges.

Previous work on MT static shift corrections falls roughly

in the following six categories: (1) Spatial filtering method using closely-spaced MT sites, which is called electro-magnetic array profiling (EMAP) (Torres-verdin and Bostic, 1992). This method is effective for the static shift correction, but its cost is high. (2) Theoretical calculation of the static shift from buried-surface inhomogeneities (Wannamaker, 1984a). This method provides considerable physical insight into the static shift, but no sufficient information about the near-surface inhomogeneity can be obtained in advance, and the calculation is too expensive. (3) Theoretical calculation of the static shift from surface topographic effects (Wannamaker, 1986). This method is incapable of dealing with the static shift due to the subsurface bodies. (4) Interpretation based on known geology. (5) Direct correction of static shifts using inversion method (Meju, 1996; Ogawa and Uchida, 1996; deGroot-Hedlin, 1995, 1991). (6) Correction of static shifts by increasing the dipole length measuring electric field, by averaging local apparent resistivities, and by using the local high conductive layer.

MT static shift is essentially a current channeling related to 3-D inhomogeneities, and the amount and direction of the shifts depend on the conductivity of the 3-D bodies.

The difficulty in the calculation of MT is due to the unknown shape and position of the 3-D bodies, therefore, it is difficult to correct the static shifts by calculation of 3-D bodies (such as Wannamaker (1984a, b)). Traditional correction of

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static shifts is to locate an effective means to deal with the indefinite surface 3-D bodies. If there is no useful information, the correction of static shifts, which has been further developed by combining previous information obtained at surface, is to shift the doubtful apparent resistivity curve to a reference curve determined by some statistics or by some criteria (such as Jones (1988), Beamish and Travassos (1992)). However, in this case, an accurate correction of static shifts is hard to obtain. The work of Sternberg's (1988) and Pellerin and Hohmann's (1990) correction of MT static shifts using central-loop TEM apparent resistivities become a milestone, for they verified the effectiveness of the method, and made TEM soundings, globally popularized, a powerful means to interpret MT data in the depth of the earth. Since the TEM sounding, only used to measure the magnetic field, is not affected by the buildup of charges at the inhomogeneity boundaries (Sternberg, 1988), the effect of the surface inhomogeneity on the TEM curves is small and, therefore, the correction of static shifts by TEM soundings is considered as an effective means. Now this correction method, noted in China, has attracted many scholars and researchers, but the related reports are few and only limited to the correction of static shift using TEM apparent resistivity curves as reference. Furthermore, the accuracy in the calculation of the corresponding data is very difficult to obtain, for the definition of the TEM apparent resistivity is very complicated. The early or the late apparent resistivity, whose error is relatively large, is often used to make an approximate interpretation. Therefore, if TEM apparent resistivity is directly applied to the correction of MT static shifts, the unreliable results are bound to occur. In addition, in this correction method, the apparent resistivity in time-domain TEM sounding is transformed into that in frequency-domain, also resulting in some errors. In terms of the special effectiveness in the correction of MT static shifts using TEM technique without any aids of other information and also in terms of the need for the joint interpretation of multiple EM data, the authors have developed an approximate inversion of TEM data (Yang and Lin, 2000), where only the measured magnetic fields which are less affected by surface inhomogeneity, instead of apparent resistivities, were used for inversion. The TEM inversion results are used to create the model of the electrical structure whose MT apparent resistivity curve can be computed as a reference curve for correction, so that the identification and correction of MT static shifts can be actualized with TEM inversion.

APPROXIMATE TEM INVERSION

Both the forward and the inverse interpretations of models of the homogeneous half space and the layered earth are made in TEM, but the interpretation of the data from more complicated 2-D or 3-D models are more difficult to make, for the calculation of their responses are complicated and expensive. For the sake of simplification, based on the theories of smoke ring (Nabighian, 1979), people consider current lines in the earth, induced by transmitting source, as downward-moving and out-

ward-expanding current filaments which are called as images of the source current. If the size, shape and magnetic moment of the images are thought of as the same as those of the transmitting source, the image depth can be determined by comparing the vertical magnetic field of the current filaments with that measured near the source. And then determined image depth can be used for the estimation of the downward vertical velocity of the image using a cubic spline interpolation method. Finally, the resistivities varying with depth can be approximately estimated through a comparison between the estimated velocity of the image and the downward diffusing velocity related to resistivities in a homogeneous half space (Eaton and Hohmann, 1989). The central-loop TEM sounding technique is best adapted to the correction of MT static shifts because of its less sensitivity to the lateral resistivity variations than those of other TEM configurations (Nekut, 1987).

In this paper, the measured magnetic fields, more reliable than the TEM apparent resistivities in characterizing the electrical structure of the subsurface, are used for inversion. But, usually, the measured data from the observation system are the partial derivatives of the magnetic field with respect to time. In addition, the magnetic fields are not directly given so that they must be estimated from the derivatives. The polynomial fitting shows that the measured derivatives range from the given latest delay time to a certain delay time at which the derivatives can be negligible. Then if the following formulation (Nekut, 1987) is used

$$H_0 = \int_{\infty}^{t_0} (dH/dt)dt \quad (1)$$

H_0 at the given latest delay time can be calculated. Finally, based on

$$H = H_0 + \int_{t_0}^t (dH/dt)dt \quad (2)$$

the value of the magnetic field at any delay time during the observation can be obtained, which is also considered as the observed magnetic field.

Because the measured responses are for 1-D layered or 2-D and 3-D models, it is necessary to obtain the image depth using the fitting approach where the configurations of multiple receiver with a single source are used. The fitting of the image with the measured fields is applied to the search for a minimum of their difference (Raiche and Galagher, 1985)

$$\Delta H = \sum_{j=1}^N | H_{sj}(t_i) - H_{sj}^i(t_i, d) | / N \quad (3)$$

where N is the total number of receivers; $H_{sj}(t_i)$ is the vertical magnetic field measured at the j th receiver and $H_{sj}^i(t_i, d)$ is the vertical magnetic at the position of the j th receiver, owing to the image at the depth d beneath the source.

After the position of the image at each discrete time has been determined, the next step is to estimate the resistivities and the depth to which each resistivity value corresponds.

In a homogeneous half space, for a central-loop the diffusion velocity at the delay time t at the depth where the magnetic field's partial derivative is the maximum, i. e., at the penetration depth, is (Spies, 1989)

$$v = \frac{\gamma^{1/2}}{\sigma\mu a} \{ C_1 + (C_1^2 + 2)^{1/2} + [1 + C_1/(C_1^2 + 2)^{1/2}] \gamma C_2 \} \quad (4)$$

$$C_1 = 0.75\sqrt{\pi} \left[1 - \gamma/4 - \sum_{k=2}^{\infty} \frac{(2k-3)!!}{k!(k+1)!} (\gamma/2)^k \right]$$

$$C_2 = 0.75\sqrt{\pi} \left[1/2 + \sum_{k=1}^{\infty} \frac{(2k-1)!!}{k!(k+2)!} (\gamma/2)^k \right]$$

$$\gamma = \sigma\mu a^2/4t.$$

In (4), if the v is given, the resistivity can be estimated with the iterative fitting method. After the determination of the image position, i. e., the depth of the image, we can estimate the diffusion velocity at each delay time by using a cubic spline interpolation. It is difficult to derive the resistivity directly from the substitution of the estimated velocity for the corresponding variable in (4). When the iterative fitting method is employed, the apparent resistivity is substituted for the corresponding variable in (4) so as to obtain a velocity. Then this velocity is compared with the estimated velocity by a cubic spline interpolation in order to modify the resistivity. This comparison goes on until the fitting criterion is satisfied. Finally, using the empirical formulation, we can obtain the sounding depth

$$h_i = 0.44d(t_i) \quad (5)$$

where 0.44 is an empirical constant.

Based on the analysis above, we worked out an inversion program and tested it for the inversion of the 1-D theoretical models. The results show that the inversion effect is good (Yang and Lin, 2000).

CORRECTION OF MT STATIC SHIFTS USING TEM METHOD

MT static shifts result from the distorted electrical field with the additional field yielded by the built-up electric charges, which do not affect the magnetic field, on the boundaries of near-surface heterogeneities. In addition, TEM soundings only measure the magnetic fields, but are not affected by the local near-surface heterogeneities. Sternberg (1988) reported that, when the delay time is later than 50 μ s, the TEM apparent resistivity curve corresponding to the near-surface inhomogeneity is the same as that free of the anomaly. (In the following examples to be presented, the delay time of the data measured by the TEM instrument V5 ranges from 0.106 3×10^{-3} s to 0.844 6×10^{-2} s so that the effect of near-surface inhomogeneity can be considered negligible).

Therefore, the inversion results of the TEM data can be used as a reference to identify and correct MT static shifts.

Determination of Sounding Depth

The size of the transmitting loop depends mainly on the TEM sounding depth, and does not greatly affect the sounding curves. However, a certain overlapped length between the TEM and the MT curves is required to correct MT static shifts. Therefore, a certain TEM sounding depth should occur to guarantee the effectiveness of the correction of static shifts.

Spies (1989), who introduced a simple method to estimate the sounding depth in EM soundings, pointed out that the MT

sounding depth depends mainly on the resistivities of the earth model and on the measured frequencies, and that the sounding depths, for the layered earth and a certain measuring system depend mainly on the average conductivity which is defined as the ratio of the integrated conductance to the total thickness of the model. The average conductivity calculated as a function of the depth can also be used approximately to estimate a lower limit of the inversion depth for layered models. In frequency domain, the sounding depth is about 1.5 skin deep computed by the average conductivity and by the lowest frequency. In time domain, the sounding depth is about one diffusion depth computed by the average conductivity and by the latest delay time. In the same way, the smallest distinctive sounding depth can be estimated by the highest frequency in frequency domain or by the earliest delay time in time domain. However, above the smallest sounding depth, the conductivity thus determined is only an average conductivity. Therefore, the TEM sounding depth depends not only on the delay time and the resistivity, but also on the size of the transmitting loop expressed by its magnetic moment, and on the noise level (Spies, 1989)

$$d \approx 40(IA/\sigma)^{1/5} \quad (6)$$

In the following example, I is 7.5 A in (6); the area, A , of the loop is 100 m \times 100 m, and the average conductivity is 0.01 S/m, the estimated TEM sounding depth is about 1 000 m, and the smallest MT sounding depth thus computed is about 350 m. Therefore, there is a certain overlap, verified in the following context between the two sounding depths, and illustrating that the TEM data in the following examples can be used to correct the static shifts.

Correction of Static Shifts Using TEM Data

When the obtained TEM data are transformed into the corresponding MT apparent resistivity curves, the TEM data is located in time domain and the MT data in frequency domain. In this case, the time-axis in TEM should be transformed into the corresponding frequency- or period-axis (Sternberg, 1988).

MT skin depth is

$$\delta_{MT} = 750 \sqrt{\rho T} \quad (7)$$

TEM skin depth or penetration depth is

$$z = 1.28 \sqrt{t/\sigma\mu} \quad (8)$$

If $\delta_{MT} = z$, then

$$194/f = t \quad (9)$$

where f (Hz) refers to the measuring frequency; t (ms), the TEM delay time; 194, the constant which is called a conversion factor ranging from 150 to 200. In this paper, we use period T (s) instead of frequency f ; delay time t with a unit s instead of ms, and the constant, 200. Then equation (9) can be changed into

$$T = 5t \quad (10)$$

There are two methods to identify and correct MT static shift. The first method is performed in the following steps: (1) The apparent resistivities are obtained from the computation of TEM inversion results, or the measured TEM apparent resistivities are directly used. (2) The time-axis of the TEM

sounding curve is transformed into the corresponding frequency-axis by equation (9) or (10), and then the apparent resistivity curve in MT is compared with that in TEM for the identification of static shifts and the determination of the amount of the shifts. (3) MT static shifts are corrected. For the half-space model, this method is practical, but for the true earth model, transformation of the TEM sounding curve from the time domain to the frequency domain following equation (9) or (10) inevitably causes some errors. Therefore, the conversion factor in equation (9) or (10) should be determined in line with concrete conditions. The second correction method, especially when only the magnetic fields or their derivatives are given, is to draw up the layered earth model by TEM inversion results, and to compute the model's MT apparent resistivity curve which can be used as a reference curve to be compared with the measured MT apparent resistivity curve. In this way, the static shifts can be identified. If the overlaps show some obvious parallel displacements between the MT apparent resistivity curve derived from TEM inversion results and that of one or two polarization modes at the test site, the static shifts occur. Therefore, the correction factor can be determined from the amount of the parallel displacements so that the measured MT apparent resistivity curve is displaced to the reference curve. If

no obvious displacement occurs, no static shifts may occur. In this paper, only the second method is used. It should be pointed out that the transformation from the TEM data in time domain to the MT data in frequency domain automatically comes true without the aid of equation (9) or (10). However, equation (9) or (10), based on the observation times in TEM soundings, can help us to estimate the frequency band of the MT curve of the model derived from the TEM inversion. In this case, more accurate MT curves can be obtained in more suitable frequency bands.

Example

Pellerin and Hohmann (1990) have corrected MT static shifts with central-loop TEM sounding technique, whose theoretical example is here introduced to illustrate its effectiveness. Figure 1a and 1b, respectively, denote the theoretical models with 1-D and 3-D near-surface inhomogeneity. Figure 2a and 2b present the diagrams for static-shift correction in the two models where the smooth curves represent the undistorted response, the dotted lines refer to computed MT reference curve to which the distorted ones will be shifted, and the circles and squares, respectively, refer to the distorted YX and XY polarization models of the apparent resistivity. In these figures, if

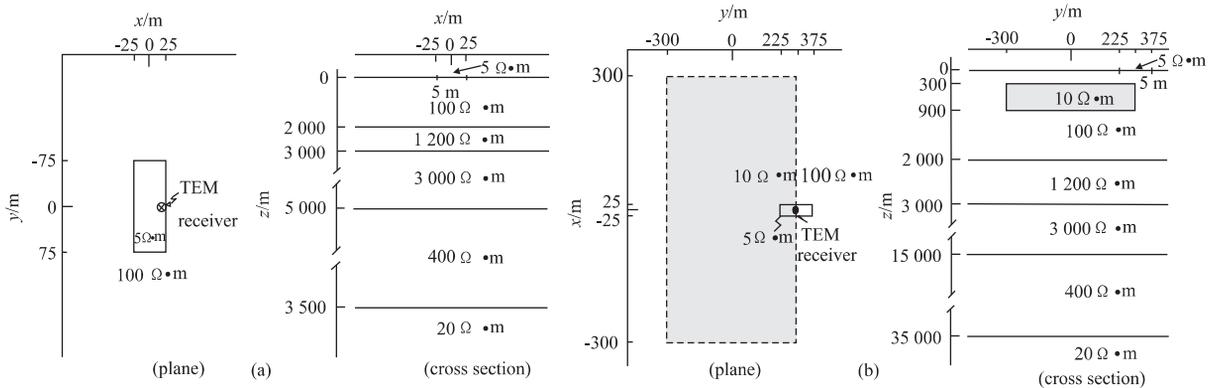


Figure 1. Model of resistivity structure. (a). model 1; a small (50 m×150 m×5 m), conductive, surficial inhomogeneity in a layered earth. The plane view shows the central-loop TEM receiver position; (b). model 2; a conductive, surficial inhomogeneity and a large, buried 3-D body in a layered earth. The layered earth and surficial body are as in (a). The stippled area represents a 10 Ω·m body embedded in the top 100 Ω·m layer. The TEM receiver location is centered on the surficial body (from Pellerin and Hohmann (1990)).

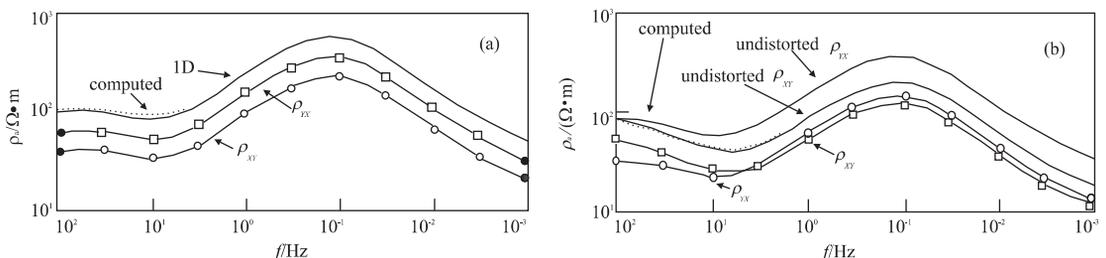


Figure 2. Diagram for static shift correction. The curves denoted by squares and circles are respectively the distorted responses for the XY and YX polarization modes, and the dotted line represents the computed correction curve to which the distorted ones will be shifted. (a). for model 1 (solid line for the undistorted 1-D response); (b). for model 2 (solid lines for the undistorted responses for two polarization modes) (from Pellerin and Hohmann (1990)).

both the distorted and undistorted curves are parallel to each other, there occurs an obvious static shift. The dotted line (serving as the reference curve) almost overlaps the undistorted curve at a high frequency band. Only parallel shifts to the reference curve serve as the terminals of the correction of static shifts, illustrating that the correction scheme obtained with the TEM technique works well.

Figure 3 shows the apparent resistivity curves of an MT sounding at Yuzhong Xiakou (E longitude $104^{\circ}01.0'$, N latitude $35^{\circ}49.0'$), southeast of Lanzhou, in 1997. The Physical Prospecting Company, the First Exploring and Designing Institute, the Ministry of Railway, joined together to make a TEM sounding along a profile at the MT site using TEM instrument, V5, with a $100\text{ m} \times 100\text{ m}$ square loop, where the receiver is distributed along the line across the center of the loop. The current in the loop was 7.5 A , and the delay times at the measured site changed from 0.1063×10^{-3} to $0.8446 \times 10^{-2}\text{ s}$ with the fixed parameters of the measurement system. In order to test our program for TEM inversion, only the data at the square loop center can be used for the program work only on the condition of a circular loop. Since the magnetic field at the center of a square loop can be equivalent to that at the center of a circular loop with the same area, from $\pi r^2 = a^2$, i. e., $r = a\pi^{-1/2}$, the inversion scheme in the paper can be applied to the data at the center of the square loop. The inversion results thus obtained are in agreement with those of 1-D generalized inversion for TEM late-time field data (Yang and Lin, 2000). Correction of MT static shifts using TEM sounding technique must guarantee the same measurement position in the two EM soundings. Figure 4 shows the inversion results of the TEM data at such a position. The MT apparent resistivity curve computed for the model derived from the TEM inversion results is denoted by the solid line which can serve as a reference curve for the static-shift correction in Fig. 3 where the two observed MT curves at the measurement site are placed together for comparison. From Fig. 3, it can be seen that ρ_{XY} has a slight static shift, but ρ_{YX} hardly does. Comparing the reference curve with the measured data, one can determine the static shift factor which is about 0.9 for ρ_{XY} , i. e., one can shift the ρ_{XY} multiplied by 0.9 to the reference curve.

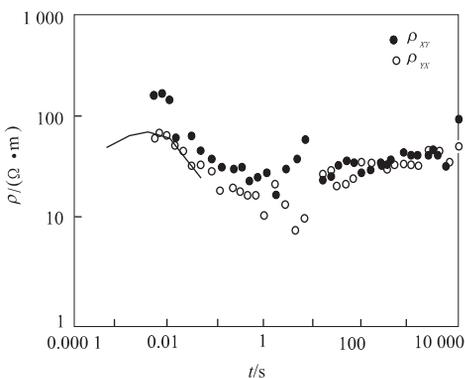


Figure 3. MT apparent resistivity (solid line) computed by TEM inversion results and observed MT curves.

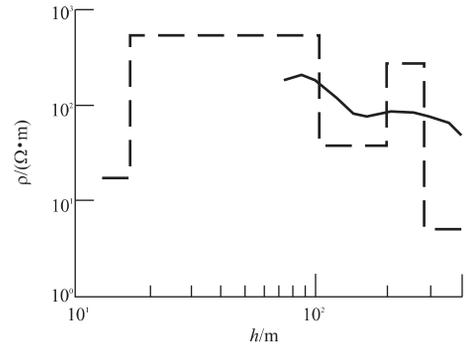


Figure 4. TEM inversion results at Yuzhong Xiakou. Solid line. inversion result in this paper; dash line. result by generalized inversion.

It should be noted that only the apparent resistivities, but not the impedance phases, are affected by the static shift. Therefore, it is not necessary to correct for the phases (Jones, 1988).

CONCLUSIONS

(1) In this paper, the identification and correction of the MT static shifts are introduced using TEM inversion where the derivatives of the measured magnetic fields are employed, instead of TEM apparent resistivities that have not been accurately defined. Therefore, the errors, caused by the TEM apparent resistivities in inversion, can be avoided. Meanwhile, the troubles of the conversion of the two EM data from time- to frequency-domain and errors caused by the conversion can also both be eliminated.

(2) The inversion results by fitting the magnetic fields of the source image with the measured fields respond less to the surface inhomogeneity. In this case, the reference curves for MT static-shift correction derived from TEM inversion results become more reliable and the MT static shift correction also turns more reliable.

(3) Compared with the correction scheme using joint inversion of TEM and MT data, the correction scheme involved in this paper has no necessity to choose which one of the two apparent resistivities will be applied to the inversion.

(4) The real example shows that the static-shift correction scheme stated in this paper, simple, easy, practical and effective, can be made on a PC in no more than one minute. In addition, this static-shift correction scheme is convenient for the interpretation of the data in the field.

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