MAGNETIC SIMULATION FOR POSSIBLE CAUSES OF THE VANISHING OF THE HIGH MAGNETIC ANOMALY BELT IN CENTRAL TAIWAN

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ABSTRACT

A striking high magnetic anomaly belt (HMAB) trending almost SW-NE is situated along the continental shelf edge off the southeastern Chinese continent. It extends northeastward to central Taiwan and gradually vanishes there. In this paper, magnetic simulation is performed and compared with other geological and geophysical data to establish a better understanding of the nature of the magnetic source of HMAB and how it makes HMAB vanish. The magnetic simulation was performed with a geometrical constraint from the seismic velocity structure published in literature. Our simulation shows that there is a layer of material with high magnetic susceptibility (which should be the source of HMAB), situated near the center of the thick crust, along the trend of HMAB. This source layer should be the magmatic relic intruded along the continental shelf edge off the Chinese continent during the initial stage of the opening of the South China Sea. The change in physical conditions or large-scale dislocation of the source material due to intensive and complicated crustal deformation are concluded to be the possible causes of the gradual vanishing of HMAB near its northeastern end.

I. INTRODUCTION

In order to provide the magnetic anomaly map for the tec-

tonic structure study conducted in the Taiwan region (Fig. 1), Hsu et al. (1998) used all the existing available magnetic data to compile a magnetic anomaly map of the Taiwan region. However, most of the on-land area on the map was blank due to limited available island-wide on-land data. Therefore, an island-wide magnetic survey was conducted for almost four years (Wang et al., 2002) to fill the blank land area. A magnetic anomaly map (Fig. 2) of the Taiwan region was thus obtained and integrated from offshore and onshore magnetic data (Hsu et al., 1998; Wang et al., 2002). From Fig. 2, it is obvious that there exists a striking high magnetic anomaly belt (HMAB; in red color; its northeastern section is marked in the box, which indicates the study area of this paper) in the southwestern Taiwan region and it trends almost SW-NE along the continental shelf edge off the southeastern Chinese continent. The HMAB has been considered the result of the magmatic intrusion along the continental shelf edge during the initial opening stage of the South China Sea (e.g., Yeh et al., 2005, 2008, 2012). It extends northeastward to central Taiwan and gradually vanishes there (see the box in Figs. 2 and 3). Thus, the depth at which this magnetized relic of intruded material is situated and how it makes the HMAB vanish in central Taiwan are intriguing questions. In this study, we conduct magnetic simulation to understand the nature of the magnetic source of HMAB. Then, we compare the model of the magnetic simulation and HMAB itself with related geophysical and geological data to study and discuss the possible causes of the gradual vanishing of HMAB in central Taiwan.

II. RELATED GEOLOGY

The plate tectonics of the Taiwan region (Fig. 1) are complicated. In the southeast, the Philippine Sea plate moves generally northwestward and with respect to the Eurasian plate, but subducts to the north in the eastern offshore area of Taiwan beneath the continental Eurasian plate. In the southern Taiwan area and to the south of Taiwan, the South China Sea oceanic lithosphere, which has been formed by a complex spreading process as a part of the Eurasian plate, subducts to the east
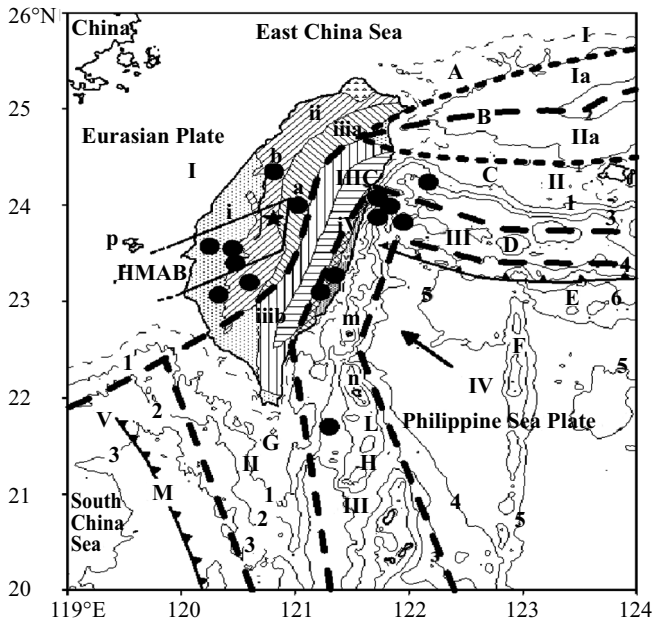
Fig. 1. The tectonic environment of the Taiwan region. The provinces on the Taiwan island are i: Western Coastal Plain; ii: Western Foothills; iiia: Hsueshan Range; iiib: Western flank of Central Range; iiic: Eastern flank of Central Range; iv: Longitudinal Valley; v: Coastal Range. The Eurasian and Philippine Sea plates are designated by I and IV, respectively. The tectonic units surrounding Taiwan are A: Continental shelf-slope of the East China Sea; B: Okinawa trough; C: Ryukyu island arc; D: Yaeyama forearc ridge; E, M: Ryukyu and Manila trenches (solid lines with triangles designate the surface fronts of the subducting Philippine Sea plate and South China Sea subplate); F: Gagua ridge; G: Hengchun accretionary prism; L: Luzon island arc; m: Lutao islet; n: Lanhsu islet; p: Penghu islets; Bathymetric contour lines are in 1000 meters except for the dashed line which designates 200 meters. Superposed are epicenters of damaging earthquakes since 1900. The black dots are those listed in Cheng et al. (1999). The star indicates the area affected by the Chi-Chi earthquake that occurred on September 21, 1999 in central Taiwan. The solid curve on the western boundary of the Western Hills represents surface rupture caused by the Chi-Chi earthquake. The parallelogram frame shows the northeastern end of the high magnetic anomaly belt (HMAB) in central Taiwan. The arrow off eastern Taiwan indicates the movement direction of the Philippine Sea plate. The bold dashed curves separate tectonic zones discussed in Wang et al. (2002).

beneath the Philippine Sea plate. Between these two subduction systems is the Taiwan island as the transition zone, on which vigorous orogeny is still underway due to the 1999 Chi-Chi earthquake in central Taiwan, which caused extensive surface ruptures (Fig. 1; Chung and Shin, 1999; Lee et al., 1999; Liu et al., 1999; Rau et al., 1999; Wang et al., 2000); this is a vivid example.

The Taiwan orogeny is obviously the result of the oblique lithospheric convergence or collision of the Philippine Sea and Eurasian plates; "oblique" because the north-south trending western front of the former "collides" the boundary of the latter represented by the almost SW-NE trending HMAB (Figs.
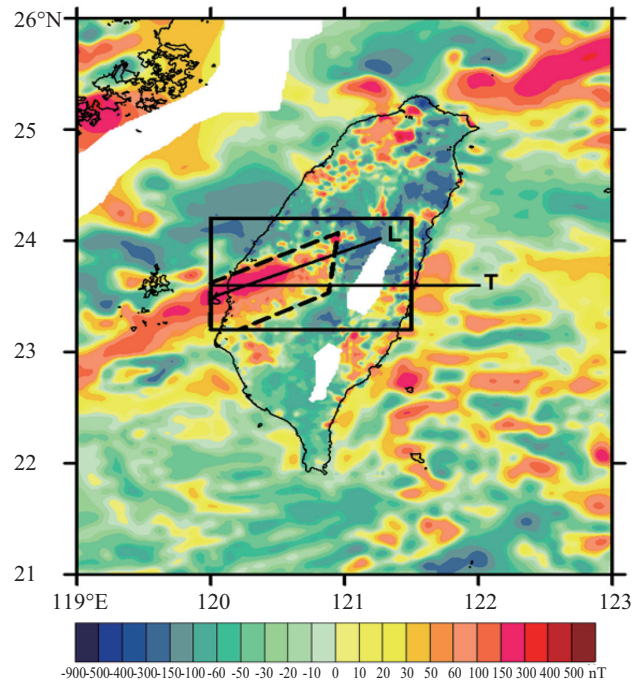

Fig. 2. Magnetic anomaly map of the Taiwan region (Wang et al., 2002). The box indicates the study area of this paper. In the southwestern Taiwan region, there exists a high magnetic anomaly belt (HMAB). Its northeastern section is marked by dotted lines in the box, drawn almost along the contour line of the magnetic anomaly of 50 nT, without exactness, just for convenience to refer to the position of HMAB in this paper. Lines T and L indicate the location of the profiles of magnetic anomaly in the E-W direction and along the HMAB trend, respectively, which are studied in this paper.
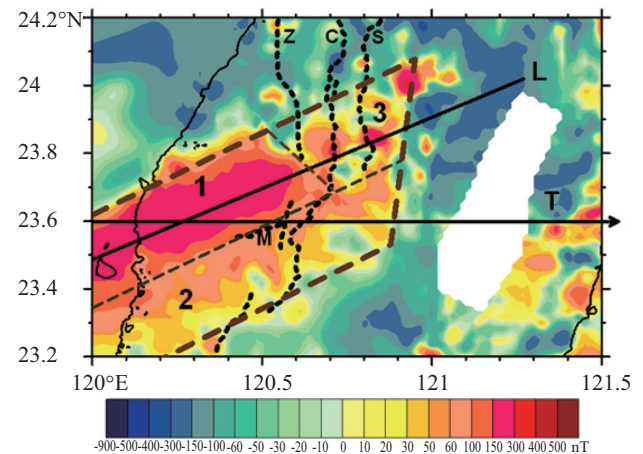
Fig. 3. The magnetic anomaly map in the study area (the box in Fig. 2). The HMAB is further divided into roughly three areas to facilitate the discussion, with area 1 covered by a magnetic anomaly higher than 100 nT, and areas 2 and 3 covered by a magnetic anomaly mainly between 50 to 100 nT. To indicate the location of magnetic anomaly profiles studied in this paper, Lines T and L are superposed. Also superposed are the surface traces of the active faults: the Damaopu-Shuangdong Fault (大茅埔–雙冬斷層), Chelungpu Fault (車籠埔斷層), Zhanghua Fault (彰化斷層), and Meishan Fault (梅山斷層), which are designated by S, C, Z, and M, respectively.

Fig. 4. Profiles of magnetic anomaly (a) in the E-W direction along latitude 23.6°N (line T in Figs. 2 and 3) and its corresponding magnetic inversion model (b). Also shown are the corresponding velocity perturbation (c) and topography (d) for comparison. In (a), the observed and calculated magnetic anomalies are designated by red and blue dotted curves; HMAB: the high magnetic anomaly belt; lines h and p are superposed to separate different parts of Fig. 4; see text for description. In (b), S designates the surface layer of the crust, Cx the magnetized 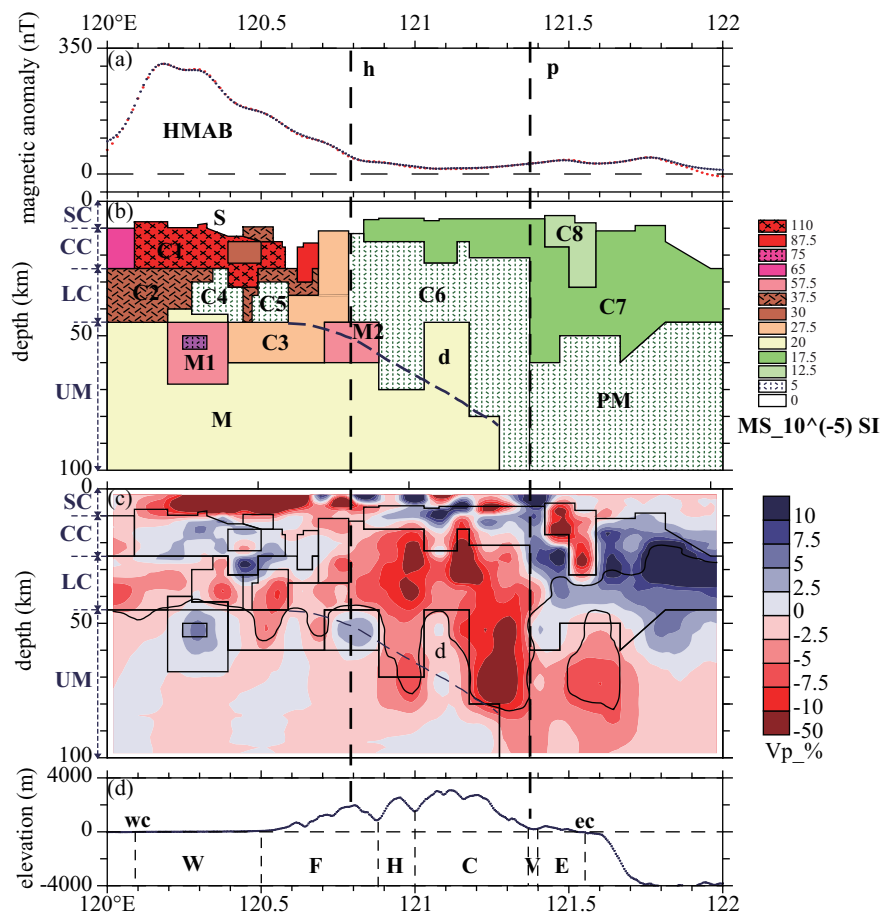polygons of the central and lower crusts, Mx the polygons of the upper mantle, and PM the upper mantle of the Philippine Sea Plate. The magnetic suscepti-bility value of each polygon is drawn to a scale on the right side. In (b) and (c), the bold dashed line near the crust/mantle boundary implies the general dipping of the upper continental mantle. In (d), wc and ec designate the western and eastern coastal lines of Taiwan; W designates the Western Coastal Plain; F indicates the Western Foothills; H indicates the Hsueshan Range; C denotes the central Range; and V and E designate the Longitudinal valley and Coastal Range of Eastern Taiwan, respectively. (See text for further information.)

1 and 2) (Wang et al., 2000, 2002; Wang, 2012), which is be-lieved to be induced by the magmatic relic formerly intruded in the beginning stage of the spreading South China Sea (e.g., Yeh et al., 2005, 2008, 2012). The arc-continent collision (Barrier and Angelier, 1983; Teng, 1990; Lundberg et al., 1997; Huang et al., 1997, 2000; Chang et al., 2000) and arc-arc col-lision (Hsu and Sibuet, 1995) are two theories to explain the mechanism of the Taiwan orogeny. Irrespective of which theory one uses to describe the orogenic phenomena, kine-matically, the oblique convergence of the Philippine Sea and Eurasian plates has resulted in the squeezing and shortening of tectonic belts (separated by the bold broken lines in Fig. 1) near the "collision site"; this collision site has been shifting southwestward along the HMAB (for detail description, see Wang et al., 2002). The HMAB is terminated near the center of Taiwan (Fig. 1); therefore, in this paper, we discuss the causes of its vanishing in terms of the Taiwan orogeny.

III. GENERAL DESCRIPTION OF THE MAGNETIC SIMULATION METHOD

An island-wide on-land magnetic survey was conducted during the period from 1997 to 2001 (Wang et al., 2002), which makes the study of the distribution of magnetized ma-terial beneath Taiwan by magnetic simulation possible. In order to understand how the HMAB vanishes at its north-eastern end, we performed magnetic anomaly in central Tai-wan. The main purposes of the simulation are to understand if any layer of material with high magnetic susceptibility exists beneath the HMAB (the magnetic source of HMAB), and, if so, what is its attitude and behavior in central Taiwan in the con-text of the vanishing of the HMAB near its northeastern end. First, we performed magnetic simulation (Fig. 4) of a profile of magnetic anomaly (solid line T in Figs. 2 and 3) in the E-W direction, across the HMAB and the structural provinces of
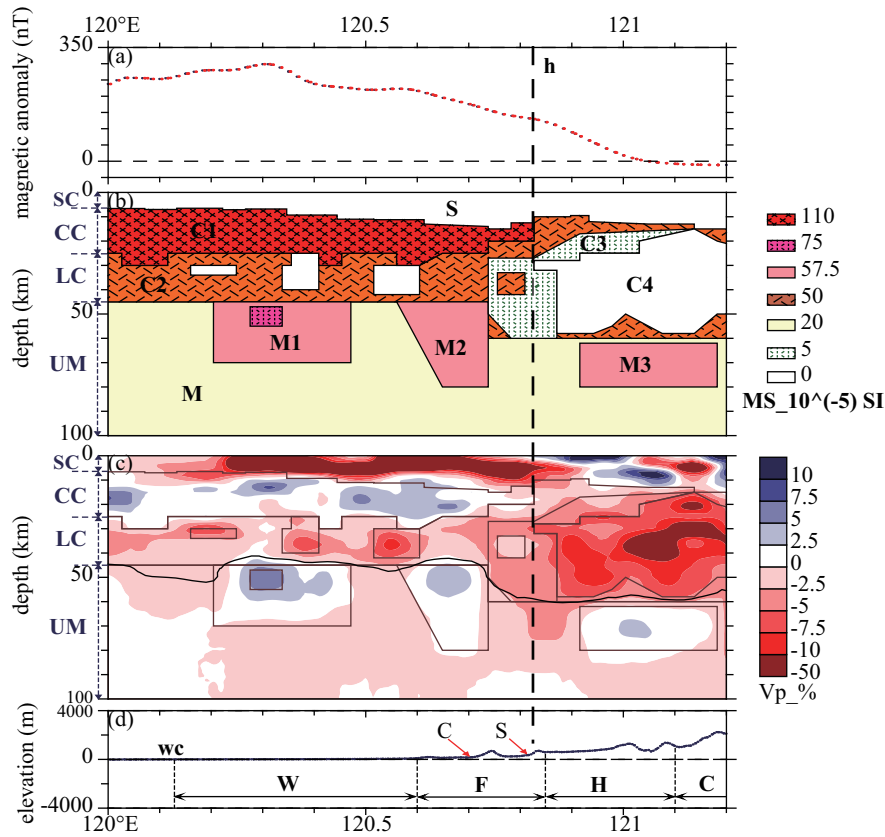
Fig. 5. Profiles of magnetic anomaly (a) along the trend of HMAB (line L in Figs. 2 and 3) and its corresponding magnetic inversion model (b). Also shown are the corresponding velocity perturbation (c) and topography (d) for comparison. Line h separates the two parts of Fig. 4 with different patterns in profiles of magnetized polygons (b) and velocity perturbation (c). The symbols are the same as those in Fig. 4, except for c and s in (d) which indicate the position of the Chelungpu and Damaopu-Shuangdong Faults. (See text for further information.)

Taiwan (see Fig. 1 for the location and attitude of the provinces), to compare the distribution of magnetic susceptibility of material beneath central Taiwan with the location of structural provinces. Then, we performed the simulation (Fig. 5) of the profile in the HMAB trend (solid line L in Figs. 2 and 3) to understand the relationship between the magnetized material and the vanishing of the HMAB at its northeastern end.

We used the computer program Mstr2d—offered by Professor Shu-Kun Hsu of Department of Earth Sciences, National Central University at Jhongli, Taiwan, rewritten with subroutine provided by Won et al. (1987) based on the method of Talwani and Heirtzler (1964)—to compute the theoretical (i.e., calculated) magnetic anomaly at surface points, along a profile, contributed by every single 2-D magnetized polygon in the model. To construct a reasonable 2-D model of magnetized polygons required by the computer program Mstr2d, we need suitable geometrical constraints from other geophysical or geological data. Wu et al. (2007) established a comprehensive data set pertaining to the 3-D P-wave seismic velocity structure beneath Taiwan (i.e., model of spatial distribution of the P-wave velocity; simply referred to as velocity structure in this paper to facilitate the discussion) using the tomographic method based on all the available P and S wave travel times together

with S-P times (i.e., the differences between the S and P arrival times) observed on seismograms of the CWBSN (Central Weather Bureau Seismic Network) and TSMIP (Taiwan Strong Motion Instrumentation Program) stations, which are operated by the Central Weather Bureau of Taiwan. This data set of velocity structure has better resolution than other existing models (Rau and Wu, 1995; Ma et al., 1996; Cheng, 2000; Kim et al., 2005) using the tomographic method, and therefore reflects more detailed crustal structure beneath Taiwan. In this study, we used this velocity structure to constrain the geometry in order to establish the magnetized polygons for the magnetic simulation.

First, we calculated and plotted the profile of the P-wave velocity perturbation structure (simply referred to as velocity perturbation in this paper; Figs. 4(c) and 5(c)) from the velocity structure data set provided by professor Yih-Min Wu of Department of Geosciences, National Taiwan University at Taipei, Taiwan (Wu et al., 2007). On the velocity perturbation profile, we drew polygons (mostly blocks, similar to those in Figs. 4(c) and 5(c)) according to different colors (representing different ranges of velocity perturbation value), and used the polygons as the geometry of our first 2-D model of magnetized polygons (similar to Figs. 4(b) and 5(b)) required by the com-

puter program Mstr2d. To fit the curve of the observed magnetic anomaly (the red dotted curve in Figs. 4(a) and 5(a)), we first assigned a suitable set of magnetic susceptibility values to the first 2-D polygons depicted from the velocity perturbation, and accordingly calculated the magnetic anomaly values for a global and general fitting. Then, we gradually adjusted the values of the magnetic susceptibility of the magnetized polygons and/or the shape of the polygons; the fitting process was conducted using the manual trial-and-error method. In the process of simulation, big and deep magnetized polygons were used to simulate long wavelengths of the magnetic anomaly, and small polygons were designed to simulate short wavelengths. In order to achieve even better fitting, we added small polygons according to the detailed velocity perturbation pattern presented in Figs. 4(c) and 5(c). According to the comparison of the curves of the calculated magnetic anomaly values (blue dotted curve in Figs. 4(a) and 5(a)) and the observed values (red dotted curve), the fitting is very good; the curves almost coincide.

Based on the geometrical polygons depicted from the velocity perturbation, it is interesting to note that it is not difficult to find a set of magnetic susceptibility values to globally and generally fit a profile of observed magnetic anomalies, and that, in the detailed fitting of the observed data, only a little change needs to be made in the geometrical polygons. This implies that the velocity structure of Wu et al. (2007) is an important and useful geometrical constraint in our magnetic simulation. It is also interesting that beneath the HMAB (the band of high magnetic anomaly shown in Figs. 4(a) and 5(a)), there is an almost horizontal layer with velocity perturbation higher than its neighborhood above and below (Figs. 4(c) and 5(c)), and this layer coincides with a layer of obviously higher magnetic susceptibility (Figs. 4(b) and 5(b)). Thus, this layer is considered as the magnetic source layer of the HMAB.

IV. MAGNETIC SIMULATION MODELS AND INTERPRETATION

Here, we discuss the results of the magnetic simulation described in the previous section. Since we set the goal for understanding the nature of the gradual vanishing of the HMAB in central Taiwan, we emphasize the simulation results beneath the HMAB; the results for elsewhere will be discussed only briefly. First, we discuss the model in the E-W direction, which crosses the HMAB and the structural provinces of Taiwan in central Taiwan. Then, we discuss the model along the trend of the HMAB.

1. Crossing the HMAB and structural provinces of central Taiwan

Model T (Fig. 4(b)) presents the simulation results of the observed magnetic anomaly profile (the red dotted curve in Fig. 4(a)) in the E-W direction (see its position marked by line T in Figs. 2 and 3). We took the geometrical polygons required by the computer program Mstr2d by dividing the cross-section of the velocity perturbation (Fig. 4(c)) into areas according to

different velocity perturbation value ranges. A contour line of 7.8 km/s of P-wave velocity (Vp), which indicates the possible position of crust/mantle boundary, was superposed on Fig. 4(c) for reference. This reference line is almost horizontal and approximately 45 km in depth beneath the Western Coastal Plain of Taiwan (Fig. 4(d)). It begins to dip (with reliefs) to the east, in general, beneath the Western Foothills, and shakes wildly, between 45 and 85 km in depth, beneath the Hsueshan and Central Ranges (Fig. 4(d)) in central Taiwan. The velocity perturbation pattern and the superposed curve of Vp 7.8 km/s (Fig. 4(c)) discussed above indicate, in general, that there exists a continental crust—approximately 45 km thick—beneath the Western Coastal Plain, which rides on the upper mantle that dips to the east beneath the Western Foothills and the Hsueshan Range, as a part of the east-dipping continental plate lithosphere. Studies using seismic data, from artificial and earthquake sources, recorded by onshore/offshore receivers (e.g., Shih et al., 1998; Yeh et al., 1998; Hao et al., 2012) displays the same characteristics as that of the crust structure. The eastward dipping of the upper mantle suggests that a part of the subducted continental plate lithosphere still remains beneath central Taiwan.

In order to well include both contributions of the crust and the mantle in the calculated magnetic anomaly, we performed the simulation of profile T with a total thickness of 100 km (Fig. 4(b)). The upper mantle (designated by M, M1 and M2... etc. in Fig. 4(b)), whose upper boundary was roughly depicted from the contour line of Vp 7.8 km/s superposed on Fig. 4(c), is important in the simulation because it is a vast area that determines the base line of the calculated magnetic anomaly curve. We assumed that its rocks are paramagnetic, and the magnetic susceptibility value of 20×10^{-5} SI was assigned to its most part (polygon M). There are some smaller polygons (such as M1 and M2) near the upper boundary of the mantle (Fig. 4(b)) with higher velocity perturbation than its neighborhood (Fig. 4(c)), to which we assigned a magnetic susceptibility higher than that of polygon M.

According to the velocity perturbation distribution of Fig. 4(c), we divided the crust beneath HMAB into three layers, the surface layer SC, central layer CC, and lower layer LC. Layer SC (which is polygon S in Fig. 4(b)) represents the upper crust and may consist of sedimentary rocks, to which we assigned the magnetic susceptibility value of 0 SI. Following the modeling process described above, except for the two polygons (M of the mantle and S of the surface layer SC of the crust) with the aforementioned values of magnetic susceptibility, we assigned suitable magnetic susceptibility values to other polygons and then adjusted these values or added a few small polygons or changed the shape of any polygon to fit the observed magnetic anomaly presented in Fig. 4(a) (the red dotted curve). We found that the theoretical magnetic anomaly (the blue dotted curve of Fig. 4(a)) calculated from the magnetized polygons of Fig. 4(b) can fit the observed values very well.

In the final model (Fig. 4(b)), the simulated values of magnetic susceptibility of most polygons in the central layer (layer CC, such as C1) beneath HMAB are 3-5 times greater as those

in layer LC (such as polygon C2) and the mantle. Thus, layer CC is believed to be the source layer of HMAB, which may be the relic of magmatic rocks along the continental shelf edge, intruded and magnetized during the initial stage of the opening of the South China Sea (Yeh et al., 2005, 2008, and 2012).

According to the patterns of the inverted model (Fig. 4(b)) of magnetic anomaly and velocity perturbation (Fig. 4(c)) on their profiles in the E-W direction along latitude 23.6°N, Fig. 4 can be divided into three main parts, separated by lines h and p. The western portion is actually HMAB itself (Fig. 4(a)) on the Western Coastal Plain and the Western Foothills (Fig. 4(d)). The crust in this portion can be vertically divided into three almost horizontal layers, with the central layer (layer CC) having obviously high magnetic susceptibility (Fig. 4(b)), which is considered as the source layer of HMAB. On the eastern edge of this part, it appears that there exists the anomalous polygon C3 (Fig. 4(b)), which penetrates from the upper mantle (polygon M) through layers LC and CC and behaves as the eastern boundary of HMAB (Figs. 4(a) and 4(b)).

The central portion includes the eastern Western Foothills, the Hsueshan Range, and the Central Range (Fig.4(d)). In this portion, the crust and upper mantle have experienced tremendous deformation and rupturing, which is implied by the complex velocity perturbation, the wild shaking of the superposed curve of Vp 7.8 km/s (Fig. 4(c)), and dip to the east in general, with a steep slope of the crust mantle boundary (as implied by the bold dashed line). It may be strained by the stresses caused by the collision between the Philippine Sea and Eurasian plates (Fig. 1) and the loading of high mountains. An interesting phenomenon is that the distinct layers CC and LC of the crust in the western portion (beneath the Western Coastal Plain and the western Western Foothills) are missing here, replaced mainly by a thick relative low velocity zone (Fig. 4(c)), which is simulated inverted in the magnetic simulation as a zone with a relatively low magnetic susceptibility (polygon C6 in Fig. 4(b)). Another interesting phenomenon in this portion is the uprising mantle dike (designated by d in Fig. 4(b)) that is approximately 25 kms high, from the mantle into the crust (polygon C6 in Fig. 4(b)). Above this dike is the almost vertical Central Range conductor (i.e., a zone of resistivity low) in the subsurface resistivity structure in central Taiwan (Chen et al., 2007), which was obtained from a Broadband Magnetotelluric Transect survey. This conductor may correspond to a vertical zone with fluids/enhanced temperature (Chen et al., 2007). The electric conductor and the mantle dike separate the Hsueshan Range and the Central Range and the crust beneath them.

The eastern portion includes the Coastal Range and the Longitudinal Valley of eastern Taiwan. In this portion, there exists a striking oceanic lithosphere (polygon PM in Fig. 4(b)) subducting northward beneath northeastern Taiwan (e.g., Rau and Wu, 1995; Ma et al., 1996; Kim et al., 2005; Wang et al., 2012), covered by a crust that is approximately 45 km thick (polygons S, C7, and C8 together). There appears to have been an obvious western boundary (drawn as line p in Fig. 4) in this oceanic lithosphere.

2. Along the Trend of HMAB

Following almost the same modeling process used for profile T (Fig. 4) across HMAB, just discussed above, we performed the simulation for profile L of the observed magnetic anomaly (the red dotted curve on Fig. 5(a)) along the HMAB trend (line L in Figs. 2 and 3) to obtain model L (Fig. 5(b)). The crust beneath HMAB was also divided into three layers (surface layer SC, central layer CC, and low layer LC), according to velocity perturbation (Fig. 5(c)). For the first model (similar to Fig. 5(b)) of model L, the magnetic susceptibility values of the essential polygons were kept the same as Fig. 4(b): (1) Similar to model T shown in Fig. 4(b), we fixed the magnetic susceptibility value of 0 SI to the surface layer SC of the crust and 20×10^{-5} SI to polygon M of the upper mantle, respectively. (2) Like Fig. 4(b), we assumed layer CC in Fig. 5(b) to be the source layer for the HMAB and assigned to it the same value 110×10^{-5} SI. (3) To those polygons (such as M1, M2, and M3) in the upper mantle near the crust/mantle boundary in Fig. 5(b), we also assigned the same values as model T (Fig. 4(b)). Then, we adjusted the assigned values of other polygons and the shape of any polygon to fit the observed magnetic anomaly of Fig. 5(a) (red dotted curve) to obtain the final model L of Fig. 5(b). The simulation result reveals that the theoretical magnetic anomaly values (the blue dotted curve of Fig. 5(a)) calculated from the model (Fig. 5(b)) agree very well with the observed values.

Fig. 5(b) reveals that beneath the HMAB, there also exists only one striking layer of high magnetic susceptibility (believed to be the source layer), as in the case of Fig. 4(b). In the middle crust (layer CC), this source layer is between 7 and 30 km deep and approximately 15 km thick on average. This layer thins gradually toward the northeast, like a wedge, and then terminates in central Taiwan at approximately 120.8°E, almost beneath the boundary between the Foothills and the Hsueshan Range (Figs. 5(b) and 5(d)). The thinning rate of the wedge is not uniform; it sharpens rapidly northeastward beneath the Western Foothills in central Taiwan, where active faults exist, such as Damaopu-Shuangdong Fault (大茅埔-雙冬斷層), Chelungpu Fault (車籠埔斷層), Zhanghua Fault (彰化斷層), and Meishan Fault (梅山斷層), designated by S, C, Z, and M, respectively, in Figs. 3 and 5(d), with the former three faults running mainly in the N-S direction. The thinning implies the attenuation of magnetic susceptibility or the vanishing of magnetized material beneath the HMAB.

Near the eastern end of the thinning source layer of the HMAB (polygon C1 in Fig. 5(b)), there is a dramatic change in the distribution patterns of velocity perturbation (Fig. 5(c)) and magnetic susceptibility in the simulated model (Fig. 5(b)). Line h in Fig. 5 (the same line h as in Fig. 4), superposed here to separate the two parts of different patterns, passes through the end point of the source layer. To the east of line h, layers CC and LC beneath the HMAB are mainly replaced by a large block with relative low velocity (Fig. 5(c)), which is thicker than layers CC and LC together, and is magnetically simulated
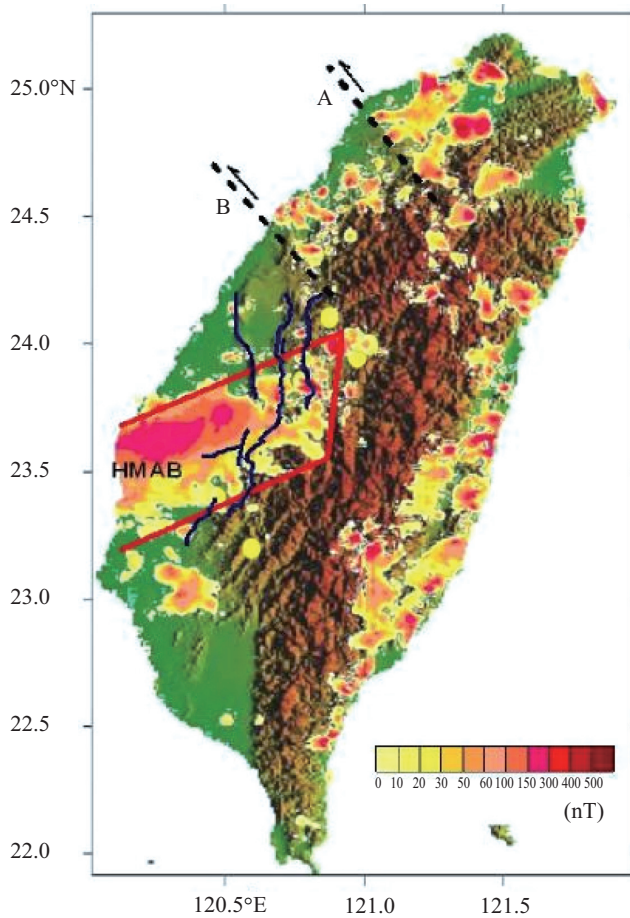
Fig. 6. Map of a positive magnetic anomaly (nT) with the topography of Taiwan and the superposed traces of active faults in the Western Foothills as background. The HMAB is marked by the red parallelogram frame; lines A and B are speculated to be shifting lines along which the magnetized material might have been removed; see text for description.
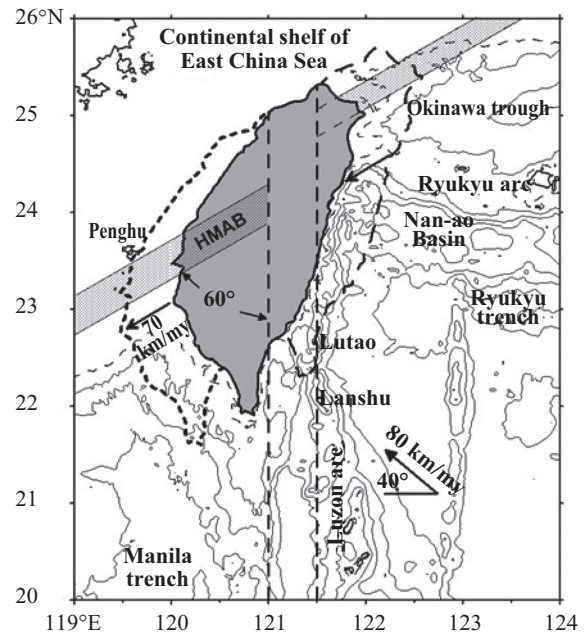

Fig. 7. Diagram showing the forming environment of the Taiwan island as a solitary wave along the Eurasian continental plate margin due to the convergence of the lithospheres of the Philippine Sea plate and the Eurasian continent plate (Wang et al., 2002). The two dashed lines along the meridian lines of 121.5°E and 121°E designate the present western boundaries of the westward underthrusting Philippine Sea plate lithosphere and the forearc sliver of this plate which is up-wrapping above the eastward dipping South China Sea plate, respectively (see description in Wang et al., 2000, 2002). The positions of the Taiwan island for different geological times with one million years apart are shown, with the present position shaded in gray. The shaded straight zones show positions of high magnetic anomaly belts southwest and northeast of Taiwan (see Wang et al., 2000, 2002 and Wang, 2012 for a detailed description).

as a collection of polygons with much lower magnetic susceptibility than layers CC and LC. Among these polygons (Fig. 5(b)), polygon C4 appears to imply that something beneath the Hsueshan Range and the Central Range of Taiwan has been squeezed into layers CC and LC of the original crust to replace them or to change the physical conditions of material to make the magnetic susceptibility vanish.

Since line h is near the western boundary of the Hsueshan Range (province iiia in Fig. 1), it implies that the complete termination of the HMAB is related to the formation of the Hsueshan Range.

V. DISCUSSION OF POSSIBLE CAUSES FOR THE VANISHING OF THE HMAB

Here, we compare the locations of the HMAB (Figs. 2 and 3) and its source layer (Fig. 5(b)) with geology and geophysics, to investigate the possible causes for the gradual vanishing and final termination of the HMAB in central Taiwan.

1. Implications of the Locations of the HMAB and its Magnetic Source Layer

From the comparison of the HMAB location (Figs. 1, 2, and 3) with the structural provinces (Fig. 1) and the topographic features of Taiwan (Fig. 6), it is evident that the HMAB occupies the structural provinces of the Western Coastal Plain and the Western Foothills (designated by i and ii, respectively, in Fig. 1), and terminates almost in the geographical center of Taiwan. According to Wang et al. (2002), the island of Taiwan behaves like a solitary wave (Fig. 7) propagating along the HMAB on the Eurasian continental plate margin off the coast of southeastern China; moreover, the northeastern end of the HMAB would always be almost at the center of Taiwan, where tectonic activity is tremendous, with a recent striking example of the 1999 Chi-Chi earthquake (Fig. 1). The reason for this tectonic solitary wave to propagate is that the site (i.e., central Taiwan) of the head-on collision between the Philippine Sea plate and the Eurasian plate is at the interaction of the western boundary of the former and the southeastern margin of the latter (represented by the HMAB); moreover, it is shifting
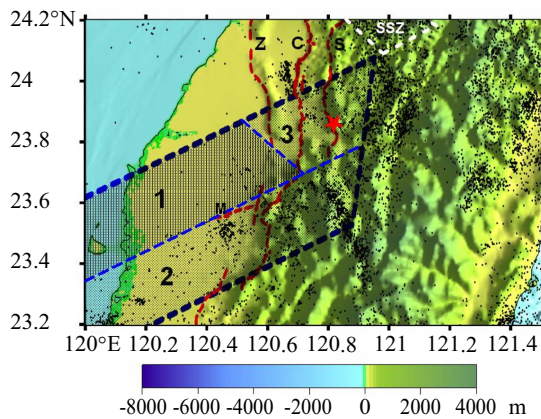
Fig. 8. The topographic map and epicentral distribution of earthquakes (Wu et al., 2007) in central Taiwan. The HMAB is marked by a bold dashed parallelogram frame and subdivided into areas 1, 2, and 3, where area 1 has rare earthquakes and areas 2 and 3 have high seismicity. Also superposed are the surface traces of the active faults: the Damaopu-Shuangdong, Chelungpu, Zhanghua, and Meishan Faults, designated by S, C, Z, and M, respectively. The star represents the Chi-Chi earthquake that occurred on September 21, 1999 in central Taiwan. The white dashed triangle frame near the top of this figure indicates the southeastern end of the Sanyi seismic zone.
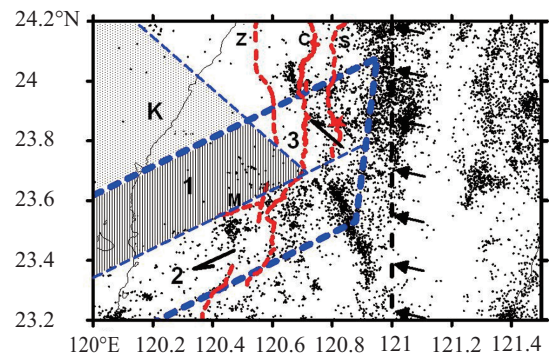

Fig. 9. Diagram showing the stress environment of HMAB (enclosed by bold dashed lines). The half-arrows show directions of material movement in areas 2 and 3 of the HMAB. The bold dashed line with arrows along longitude 121°E indicates the front of the westward-moving material above the slope of the eastward dipping Eurasian continental plate lithosphere, which is pushed upward by the collision of the Philippine Sea plate (see Wang et al., 2000 detailed description). Area 1 of the HMAB and its western neighborhood (designated by K) together correspond to the Pre-Miocene basement indicated by a zone of high magnetization (Hsu et al., 2008) or by a high velocity perturbation zone (Cheng, 2000). The traces of active faults (designated by Z, C, S, and M) are also superposed for comparison.

southwestward along the HMAB (Fig. 7; Wang, 2012; Wang et al., 2002), along with the westward advance of the western boundary of the Philippine Sea plate (with respect to the Eurasian plate). The creation of the Taiwan island is the result of the squeezing together of different tectonic zones (Fig. 1) due to the collision (Wang et al., 2002); the strongest action of the collision is currently underway in central Taiwan. Therefore, the location of the HMAB in the background of the formation of Taiwan (Figs. 1, 6, and 7) implies that the hard material beneath the HMAB can be regarded as a kerb hindering the northwestward crustal movement in the Taiwan orogeny. It also implies that the accumulated dislocation and change in physical conditions of the material beneath the HMAB caused by the Taiwan orogeny is probably responsible for the gradual vanishing of the HMAB.

From the inverted model of the magnetized polygons in Fig. 5(b) discussed in the last section, we know that the magnetic source layer of the HMAB in the middle crust gradually thins toward the northeast, like a wedge, from the western offshore area through the Western Coastal Plain and the Western Foothills in central Taiwan (Figs. 5(b) and 5(d)); moreover, it is also evident that the thinning source layer sharpens rapidly beneath the Western Foothills and then terminates almost at the geometrical center of Taiwan (Figs. 5(b) and 5(d)) beneath the western boundary of the Hsueshan Range. From the shape and location of the source layer (Fig. 5(b)), it appears that we can interpret the thinning of the source layer due to the accumulated effect of the Taiwan orogeny in this manner: The thinning not only implies the physical thinning of the source layer, but also the attenuation of the magnetic susceptibility of the magnetized material or the decreasing amount of the magnetized material in the source layer.

The northeastward thinning of the source layer may imply that the total accumulated effect of tectonic activities increases toward the east in general. The implication is confirmed by the N-S trending structural provinces in central Taiwan illustrated in Fig. 1 and the topography of Taiwan shown in Figs. 6 and 8; the terrains and mountains become higher and more complicated toward the east. The tectonic activities here refer to deforming, fracturing, faulting, and uplifting etc., which often accompany earthquakes; the degree of the accumulated effect depends not only on the magnitudes of single activities and frequency of activities, but also on the geological historical time through which these activities have occurred.

2. Tectonic Activities Implied by Seismicity

The seismicity depicted in Fig. 8 reveals that frequent earthquakes occurred in the southeastern and northeastern HMAB (i.e., areas 2 and 3 in Fig. 8), with the Chelungpu and Meishan Faults (designated by C and M, respectively; Fig. 8) roughly being the western boundary of the high seismicity. From the comparison of the seismicity (Fig. 8) with the magnetic anomaly distribution on the HMAB (Fig. 3), it is obvious that the magnetic anomaly on the southeastern and northeastern HMAB (i.e., areas 2 and 3) is much smaller than that on the northwestern HMAB (area 1 in Figs. 3 and 8), where few earthquakes occurred. Accordingto the stress model of Wang et al. (2000) for the tectonic environment of the great 1999 Chi-Chi earthquake in central Taiwan and its tremendous number of aftershocks, the hindering of the crustal movement in the front portion of the Taiwan orogeny (Figs. 6 and 7) by the hard crustal material beneath the HMAB, acting as a kerb (Fig. 9), creates a special pattern of seismicity on the

HMAB (Fig. 8); the northeastern and southeastern HMAB (areas 2 and 3 in Fig. 8), under stress, are the areas where tectonic activity—such as the deforming, fracturing, and faulting—has recently been very active accompanied by frequent earthquakes, mostly of the thrust and strike-slip types (e.g., Kao and Chen, 2000; Wang et al., 2000). According to Fig. 9 and Wang et al. (2000), the lateral component of the movement along the selected fault plane of most single earthquakes in area 2 should be in the dextral (right-hand) sense and that in area 3 should be in the sinistral (left-hand) sense to make the final displacements, as indicated by the bold half-arrows in Fig. 9. The large 1999 Chi-Chi earthquake (Figs. 1 and 8), which occurred in area 3 of the HMAB and caused large surface ruptures and crustal deformation (Fig. 1), is a vivid example of the tectonic activity that is destroying the crustal material beneath the HMAB. This tremendous earthquake can be regarded as being triggered by the breaking of hard material beneath the northeastern end of the HMAB, which acts like a strong kerb hindering the northwestward crustal movement from the east of the Chelungpu Fault (designated by C in Figs. 3 and 8). This can be envisaged from Figs. 3, 6, and 8 that the Zhanghua Fault (designated by Z in Figs. 3 and 8) fails to pass through the HMAB, while the Chelungpu Fault does penetrate the HMAB.

The locations of 16 historical destructive earthquakes (including the Chi-Chi earthquake in 1999) are superposed on Fig. 1 to indicate places where large tectonic energy was released from the crust beneath the Taiwan area. Among these earthquakes, seven occurred in the crust in or near the HMAB. This also implies that the stress due to the Taiwan orogeny is acting vividly on the hard crustal material beneath the HMAB, which can be asperity (the initiating points) for future large earthquakes in central Taiwan.

The seismicity pattern discussed is a present-time example of how the Taiwan orogeny has been acting on the material beneath the HMAB, and thus possibly changing the physical conditions of the source layer, including the change in density, diversion of the magnetization direction of the source rock particles, or migration of the magnetized rock due to faulting.

3. Resetting of Magnetic Susceptibility

One main possible cause for the gradual vanishing of the HMAB is the diminishing of the magnetized material beneath the HMAB due to the resetting of magnetic susceptibility. According to Tanaka et al. (1999), the Curie point depths are shallower than 10 km at volcanic and geothermal areas, and 15-25 km at island arcs and ridges. Therefore, the resetting of magnetic susceptibility should have been in process due to the Taiwan orogeny if fluids are present and heat supply is ample beneath the HMAB.

It is possible that the actions of the Taiwan orogeny on the crustal material beneath the HMAB created fluids, such as water from dehydrated rocks or from the ground surface (e.g., Matsubayashi et al., 2005; Chen et al., 2007; Lin et al., 2008) or magma from below are injected into the source layer, be-

cause the resulting ruptures or fissures would allow fluids to penetrate. We can presume that these ruptures or fissures exist beneath western-central Taiwan from the complicated pattern of velocity perturbation (Figs. 4(c) and 5(c)) and magnetized polygons (Figs. 4(b) and 5(b)). The injected fluids can gradually change the physical conditions of the source layer, thereby attenuating its magnetization, by actions such as liquefaction of minerals due to decreasing melting points (and thus the Curie points) from the contamination of water. The heat required for the resetting of magnetic susceptibility can be brought up by the injected magma or heat flow due to the geothermal gradient in rocks. Polygons C3, C4, and C5 in Fig. 4(b) could be the crustal material contaminated by the injected magma or water; thus, their magnetic susceptibility might have been diminished by partial melting due to increased temperature or decreasing melting points.

Since the source layer of the HMAB (Fig. 5(b)) sharpens toward the northeast under the Western Foothills (west of line h shown in Fig. 5), a dramatic change in physical conditions of the source layer was probably underway beneath the Western Foothills where active faults exist—such as the Damaopu-Shuangdong, Chelungpu, Zhanghua, and Meishan Faults (designated by S, C, Z, and M in Figs. 3, 6, and 8)—which can cause the fractures (e.g., Ma et al., 2006) to accommodate fluids that may, in turn, trigger geological events (e.g., Chen et al., 2007); a good example is the frequent earthquakes shown in Figs. 1 and 8.

4. Large-scale Horizontal Dislocation of the Source Material

Another possible cause for the vanishing or termination of the source layer of the HMAB (Fig. 5(b)) in central Taiwan is large-scale horizontal displacement or up-lifting of the magnetized material of the source layer. This is implied by the 1999 Chi-Chi earthquake, which created a large surface rupture along the Chelungpu Fault in front of the Hsueshan Range (Fig. 1), with the main rupture being approximately 85 km long in the entire central Taiwan region, with the maximum vertical uplift approximately 6 meters and horizontal displacement over 9 meters (e.g., Chung and Shin, 1999; Lee et al., 1999; Liu et al., 1999; Rau et al., 1999; Wang et al., 2000).

According to the patterns of magnetized polygons (Figs. 4(b) and 5(b)), velocity perturbation (Figs. 4(c) and 5(c)), and discussions in section IV, the block of the central part of Fig. 4 (i.e., the zone between lines h and p) should have been squeezed, shortened, and uplifted under tremendous compressional and shear stresses caused by oblique collision between the Eurasian and Philippine Sea plates. The result is that the main portion of the Taiwan orogeny was created here: the building of the Hsueshan and Central Ranges (Figs. 4(d) and 5(d)). The building mechanism includes complicated faulting systems, with both thrusting and lateral components of movement, which must have persistently removed or destroyed the magnetized material of the source layer of the HMAB in the middle of the thick crust, and the resultant large-scale dislocation

of material must have completely truncated the HMAB. Evidence to support this inference is that in the simulated model of the magnetic anomaly (Figs. 4(b) and 5(b)), the layered structure of the magnetized polygons in the western portion of the model is mainly replaced by a large polygon with low magnetic susceptibility in the central portion (between lines h and p).

In Figs. 1, 2, 3, 6, and 8, the eastern boundary of the HMAB runs almost in the N-S direction; this is near the western boundary of the Hsueshan Range (Figs. 1, 4(d) and 5(d)). Therefore, the truncation of the HMAB must be related to the formation of the Hsueshan Range in its uplifting process.

In Fig. 6, we speculated two possible horizontal shifting lines (lines A and B), along which the magnetized material in the central crust beneath the previous original portion of the HMAB may have been removed step-wise and horizontally by several tens of kilometers. The reason why we made this speculation is because there exists an offsetted zone of high magnetic anomaly on the northern Western Foothills (Fig. 6), which surrounds the Hsueshan Range on the northwestern side.

The large horizontal displacement might be the resultant accumulated displacement in the complex process of the Taiwan orogeny in geological time. The resultant movement of the opposite blocks should be in the sinistral (left-hand lateral) sense along the lines A and B, as shown by the half arrows next to the lines in Fig. 6; this is judged from the offsetting pattern of the high magnetic anomaly zone that exists in the Western Foothills in northwestern Taiwan (Fig. 6).

Line A is in an area with rare earthquakes; thus, the crustal movement along it is probably inactive. Line B corresponds to the NW-SE trending Sanyi (三義) seismic zone (e.g., Rau and Wu, 1997), which can also be seen in Fig. 8. The Sanyi seismic zone has witnessed two destructive earthquakes (designated by a and b in Fig. 1) in history; thus, there continues to be a vivid crustal movement along line B.

Of course, the accumulated displacement cannot simply have been achieved by crustal movement along certain specific shifting lines, such as lines A and B; it should have been achieved by the crustal movement in complex fault systems, including the Damaopu-Shuangdong, Chelungpu, Zhanghua, and Meishan Faults (designated by S, C, Z, and M, respectively, in Figs. 3 and 8). Taking Chelungpu Fault as an example, the 1999 Chi-Chi earthquake caused a significant horizontal sinistral movement along this active fault that is approximately 85 km long, with the fault plane dipping toward the east (e.g., Ma et al., 2001), to a depth of over 20 km (Lin and Ando, 2004). The Chelungpu Fault is suspected to meet the western boundary of the Hsueshan Range and, thus, the movement of material along this fault is suspected to play an important role in terminating the source layer of the HMAB in the middle of the crust. Cheng (2005) considered that the magnetized material beneath the northeastern part of the HMAB has been pushed northwestward, according to the velocity structure based on the tomographic method. Judging from the distribution of magnetized material in their model of magnetic simu-

lation, Chen et al. (2010) suggested that the crust of the Eurasian plate beneath the Western Foothills in central Taiwan has been uplifted, with a greater degree toward north. The results of their models imply that the dislocation of material beneath the HMAB, where active faults exist, has also been active in front of the Hsueshan Range.

VI. CONCLUSION

By the simulation of the magnetic anomaly, with the P-wave velocity structure derived by the tomographic method (Wu et al., 2007) as the geometrical constraint, we studied the magnetic source of the northeastern section of the HMAB on the continental shelf edge in central-western Taiwan to understand how the HMAB gradually vanishes in central Taiwan. We obtained the following conclusions:

1. Along the trend of the HMAB, there exists a layer of material with high magnetic susceptibility (believed to be the source layer of HMAB) in the middle of the thick continental crust, which should be the relic of magma intruded along the continental shelf edge off southeastern China during the opening stage of the South China Sea.

2. A comparison of the gradually vanishing HMAB in central Taiwan and the attitude and behavior of its source layer with seismicity, geomorphology, and fault systems implies (a) the diminishing of the magnetized material in the source layer of the HMAB caused by the increasing accumulated effect of the Taiwan orogeny is responsible for the gradual vanishing of the HMAB on the Western Coastal Plain and Western Foothills, and (b) the horizontal/vertical large-scale dislocation of the magnetized source material of HMAB due to the uplift of the Hsueshan Range in the process of its formation has completely truncated the HMAB in central Taiwan.

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