Melting features along the Ryukyu slab tear, beneath the southwestern Okinawa Trough

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[1] The present-day active volcanic front associated with the Ryukyu subduction zone extends from Japan to the Ilan plain (northern Taiwan) and is located within the Okinawa Trough, 80–100 km above the Ryukyu slab. An abnormal amount of arc volcanism, which consists of basalt, andesite and rhyolite occurs within the southwestern Okinawa Trough, above a slab tear of the Ryukyu subduction zone (CBVT). The power spectrum analysis of magnetic data shows the occurrence of a thin crust above the slab tear and a thick crust beneath this volcanic area. We suggest that an excess of H_2O-rich fluid might occur at the slab tear and might increase the melt flux. Both are conveyed obliquely to the uppermost mantle and lower crust CBVT magmas. After interactions, basaltic magmas would rise up, accounting for the contrast of magnetization between this volcanic body and the adjacent OT crust. *INDEX TERMS:* 1517 Geomagnetism and Paleomagnetism: Magnetic anomaly modeling; 7218 Seismology: Lithosphere and upper mantle; 8100 Tectonophysics; 8159 Tectonophysics: Rheology—crust and lithosphere. **Citation:** Lin, J.-Y., S.-K. Hsu, and J.-C. Sibuet (2004), Melting features along the Ryukyu slab tear, beneath the southwestern Okinawa Trough, *Geophys. Res. Lett.*, *31*, L19607, doi:10.1029/2004GL020862.

1. Geological and Petrological Settings

[2] The Ryukyu subduction zone, which extends from Japan to Taiwan, terminates westwards beneath northeastern Taiwan (Figure 1). The volcanic front (dotted gray line in the upper inset of Figure 1) also extends from Japan to Taiwan and is located within the Okinawa Trough (OT). From Kyushu to Okinawa Island, it coincides with small subaerial active volcanoes located about 25 km west of the non-volcanic arc. Southwest of Okinawa Island, it follows numerous seamounts associated with high magnitude magnetic anomalies [*Hsu et al.*, 2001], then the cross backarc volcanic trail (CBVT) which consists of a cluster of about 70 seamounts located west of 123°E longitude (lower inset in Figure 1) and finally ends at Kueishantao Island [*Chung et al.*, 2000; *Sibuet et al.*, 1998], an islet located 10-km offshore the Ilan Plain (OT tip). The volcanic front is 80–100 km above the subducted slab. The minimum slab depth of 80 km is required for the emplacement of arc magmatism [*Gill*, 1981; *Tatsumi*, 1986], explaining why the present-day Ryukyu arc is not located within the Ryukyu non-volcanic islands but within the OT.

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[3] Amongst the several tens of volcanic seamounts identified in the CBVT [*Sibuet et al.*, 1998], most of them are located in the vicinity of the axial depression. Basalts, andesites and rhyolites collected there belong to the medium-K field in the SiO_2*vs* K_2O diagram and are subalkaline [*Chung et al.*, 2000; *Shinjo et al.*, 2003a, 2003b]. Rhyolites are dominant in the CBVT. *Shinjo et al.* [2003a, 2003b] demonstrate that mafic intrusions in the CBVT rhyolites resulted from magma mixing between high temperature (high-Mg content) mafic and low temperature (low-Mg content) felsic magmas, implying a high degree of partial melting with slab components. The incompatible elements are enriched in large ion lithophile elements, Th, U and Pb and depleted in Nb, Ta and Ti [*Chung et al.*, 2000; *Shinjo et al.*, 2003a, 2003b]. Thus, the elemental and isotopic variations are compatible with magma derivation from an Indian NMORB-like source that is strongly overprinted by subduction components from the slab [*Shinjo et al.*, 2003a, 2003b]. Thus, CBVT basalts are not typical of backarc basin basalts.

2. Ryukyu Slab Tear and Seismicity

[4] Relocated earthquake hypocenters from teleseismic data recorded from 1964 to 1999 [*Engdahl et al.*, 1998] with a standard deviation less than 20 km are plotted for 50-km wide bandwidths on each side of the northern prolongation of the Huatung Basin/west Philippine (PH) Sea shear plate boundary located east of Gagua Ridge and underlined by a negative free-air anomaly trend [*Hsu et al.*, 1998] (Figures 1 and 2c). The upper envelope of these earthquakes corresponds to the top of the subducted slab. As already mentioned by *Deschamps et al.* [2000], the portion of slab located north of the Huatung Basin (A) presents a steeper dipping angle than the one located north of the west Philippine Basin (B). However, we suggest that the PH plate was torn rather than bent during the subduction process for the following reasons: (1) The Huatung Basin/west (PH) Sea plate boundary is a zone of weakness [*Sibuet et al.*, 2002]. (2) The lithospheres on each side of this boundary are characterized by different crustal thicknesses and rheologies [*Hsu*, 2001; *Murauchi et al.*, 1968; *Wang et al.*, 2002]. (3) At 25.5°N latitude, the western portion A of the Ryukyu slab is 80 km deeper than the eastern portion B of the slab (Figures 1 and 2c). (4) The slab displays different strain patterns on each side of 123.3°E [*Kao and Chen*, 1991]. We consequently suggest a link between the location of the Ryukyu slab tear and the localized excess of volcanism in the CBVT region, whose geochemical composition reflects a slab component and arc signature.

3. Depth and Thickness of the Magnetized Crust

[5] The southern Okinawa Trough exhibits low magnetization values [*Hsu et al.*, 2001] except for a relative higher

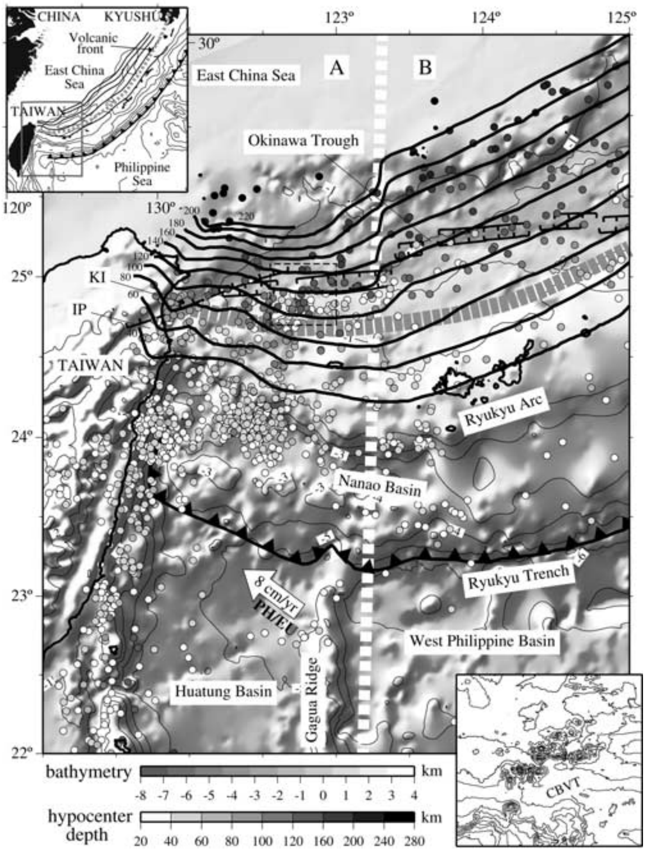

Figure 1. Bathymetry, topography (every kilometer with shading from N315°) and seismicity [*Engdahl et al.*, 1998] in the northwestern corner of the Philippine Sea plate. Dots represent earthquake hypocenters. The thick contour lines are depths of the Ryukyu slab (adapted from *Font et al.* [1999] in the western part). The dashed line shows the location of the Huatung Basin/western PH Sea plate boundary underlined by a negative free-air anomaly trend [*Hsu et al.*, 1998] and located just east of Gagua Ridge. Its northern prolongation coincides with the Ryukyu slab tear, underlined by the offsets of slab isobaths. In the upper left corner, general map of the Ryukyu subduction zone with isobaths of the Ryukyu slab every 50 km [*Sibuet et al.*, 1998]. The volcanic front is located 80–100 km above the slab. In the lower right corner, detailed bathymetry (isobath spacing, 100 m) of the cross backarc volcanic trail (CBVT) [*Sibuet et al.*, 1998] in the square box (dashed black line) located west of the slab tear. The arrow indicates the PH/EU plate motion from *Yu et al.* [1997].

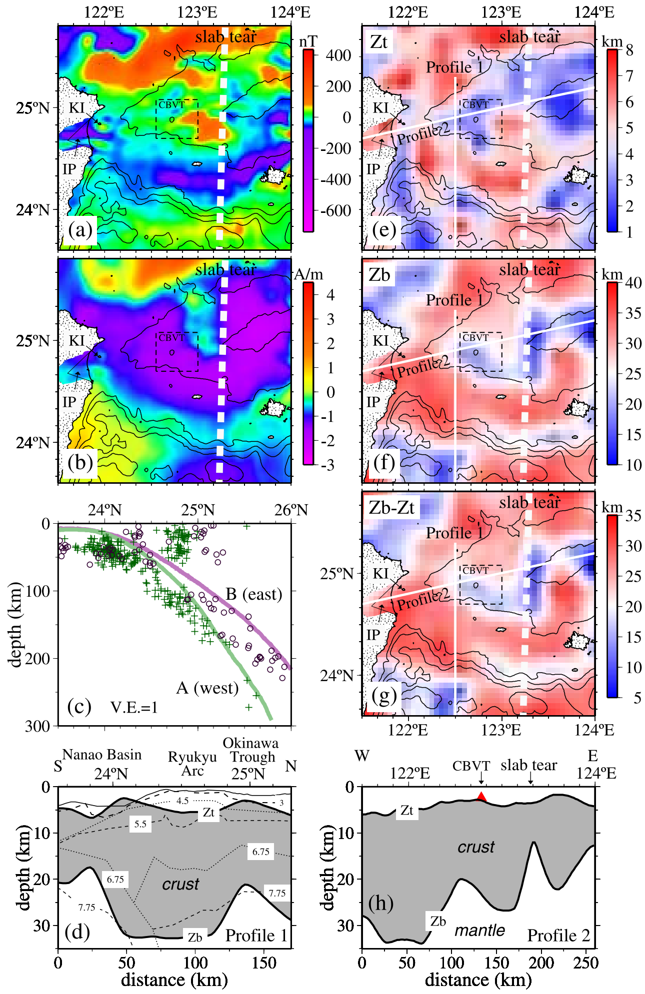

Figure 2. a) Magnetic anomalies from *Hsu et al.* [2001]. Thin black lines are bathymetric contours every kilometer. The square box in dashed black lines (CBVT, cross backarc volcanic trail) corresponds to the location of the bathymetric inset in Figure 1. b) The portion of the Okinawa Trough deeper than 1000 m is characterized by low magnetization values except for the higher magnetization zone located west of the Ryukyu slab tear (white dashed line). c) Earthquake distribution within two 50-km wide parallel stripes located on each side of the 123.3°E meridian. Crosses and open circles represent earthquakes located west and east of this limit respectively. The western portion A of the slab is steeper and deeper than the eastern portion B of the slab. d) Estimates of the depth and thickness of magnetic sources (thick lines) extracted from Figures e and f. Comparison with the P-wave velocity-interface model along refraction Profile 1 [*Wang et al.*, 2002] (thin dotted/dashed lines). e) Depth Z_t of the top of magnetic sources using the power spectrum method. Values are calculated every 0.2 degree in 60 km × 60 km data squares; f) Depth Z_b of the base (Curie point) of the magnetic sources using the same method; g) thickness of the magnetized layer (Z_b-Z_t). h) Geometry of the crust deduced from Z_t and Z_b distributions along Profile 2.

magnetization zone located between 24.9°N and 25.5°N [*Hsu et al.*, 2001] (Figure 2b), west of the slab tear. To understand the thickness variation of the magnetic source beneath the southern Okinawa Trough, we use the power spectrum technique to estimate the depths to the top (Z_t) and to the centroid (Z_0) of the magnetic source. If the wave number (k) is less than about twice the thickness of the magnetized layer, Z_t is calculated from the slope between $\mathrm{Ln}[\Phi_{\Delta T}(|k|^{1/2})]$ and $|k|$, where the $\Phi_{\Delta T}(|k|)$ is the power-density of the averaged radial spectrum of the total-field magnetic anomaly. At longer wavelengths, Z_0 is given by the slope between $\mathrm{Ln}\{[\Phi_{\Delta T}(|k|)^{1/2}]/|k|\}$ and $|k|$ [*Blakely*, 1988; *Tanaka et al.*, 1999]. The basal depth Z_b of the magnetic source, assumed to be the Curie point depth, is then calculated by $Z_b = 2Z_0 - Z_t$.

[6] In order to enhance the broad features linked to deep features, the centroid depths were calculated for wavelengths larger than 10 km [*Stampolidis and Tsokas*, 2002; *Tanaka et al.*, 1999]. Z_t, Z_b and the thickness of the magnetized crust (Z_b-Z_t) have been computed on a regular grid pattern with a 0.2 degree spacing. The size of each calculated area is 60 km × 60 km. For reasonable centroid estimates, a minimum ratio of 12 between the size of the used data square and the depth of the centroid point was established by *Okubo et al.* [1985]. Figure 2d shows a comparison between the estimated depths Z_t and Z_b with the P-wave velocity model computed from the refracted and reflected arrivals along Profile 1 [*Wang et al.*, 2002]. Z_t and Z_b correspond approximately to the 4.5 (top of volcanics) and 7.75 (Moho) km/s interfaces, which gives credit to the maps of Figures 2e–2g.

[7] The map of magnetic anomaly data (Figure 2a) shows the presence of a large magnetic body located in the axial part of the OT, west of 123.3°E and at an average depth of 3–4 km (Figure 2h). The CBVT seamounts, identified at mean depth of 1.3 km, are shallower than this estimate. This difference might be explained by the smoothing effect due to the power spectrum estimation. However, the seismic reflection [*Sibuet et al.*, 1998] and diving [*Matsumoto*, 2001] data show that the CBVT seamounts have been intruded through a 1-km thick sedimentary cover and that a significant amount of non-magnetized hydrothermal deposits exists on top of some of them. At depth, the Curie point surface (Figure 2h), which is close to the Moho surface, is about 25 km beneath the CBVT and 15 km at the vertical of the slab tear, above which no volcanism was evidenced (Figure 2g). Thus, the crust is thick beneath the CBVT and thin beneath the slab tear (Figures 2g and 2f).

4. Discussion and Conclusion

[8] In the southwestern OT, only characterized by a few thin elongated backarc basin features, the CBVT appears as an abnormal area of Recent and Present-day volcanism [*Sibuet et al.*, 1998]. In general, most arc volcanic rocks are derived from melting of the mantle wedge induced by hydrous fluids released during dehydration reactions in the subducted oceanic lithosphere [*Arculus*, 1994; *Gill*, 1981]. Melt and/or fluid flow from the underlying slab through an oblique mantle wedge and crustal pathway have been spectacularly imaged by tomographic data both beneath the Quaternary arc volcanoes of Japan [*Wyss et al.*, 2001] and beneath Kueishantao Island (J. Y. Lin et al., Melting features along the western Ryukyu slab edge (northeast Taiwan): Tomographic evidence, submitted to *Journal of Geophysical Research*, 2004, hereinafter referred to as Lin et al., submitted manuscript, 2004). The CBVT melt or fluid supply could have a westward oblique component originated from the slab tear, even if a significant part of the melt was formed within the upper mantle and lower crust, as a consequence of the OT backarc basin extension.

[9] We suggest that the deep process, which is proposed for the origin of Kueishantao Island located close to the western termination of the Ryukyu slab (Lin et al., submitted manuscript, 2004), could be applied for the CBVT, located 140 km east of the Ryukyu slab termination (Figure 3). The eastern part B of the Ryukyu slab being shallower than the western part A, two hypotheses might be proposed: (1) Abnormal heating due to the friction of the vertical portion of slab B (located above the portion of slab A) against the adjacent EU lithosphere and/or the upwelling of the underlying PH mantle material through the slab tear could induce the formation of additional melt above the slab B. However, *Rüpke et al.* [2004] suggest that shear stresses and shear heating, though largely unconstrained, are weak at the boundary between the slab and the overlying mantle and lithosphere. Thus, friction heating might be negligible. Upwelling of underlying PH mantle might only occur north of 25.5°N where the PH mantle of slab B largely culminates above slab A. Such a mantle upwelling would occur about 50 km north of the CBVT, which might require a too much oblique feeding pathway to reach the CBVT magmas. (2) Increased H_2O-rich component derived from fluids from the underlying subducting slab and slab tear might enhance the generation of CBVT magmas located in the EU upper mantle/lower crust [*Stolper and Newman*, 1994]. Backarc basin magmas worldwide are rich in H_2O relative to NMORB, so a general mechanism must exist (as an upward migration of fluids generated by deep dehydration) to account for the water enrichment. Fluid release occurs above the slabs at depths <20 km from subducting sediments, at intermediate depths (20–100 km) from sediments and oceanic crust and at depths >100 km from oceanic crust and serpentinized mantle [*Rüpke et al.*, 2004]. An

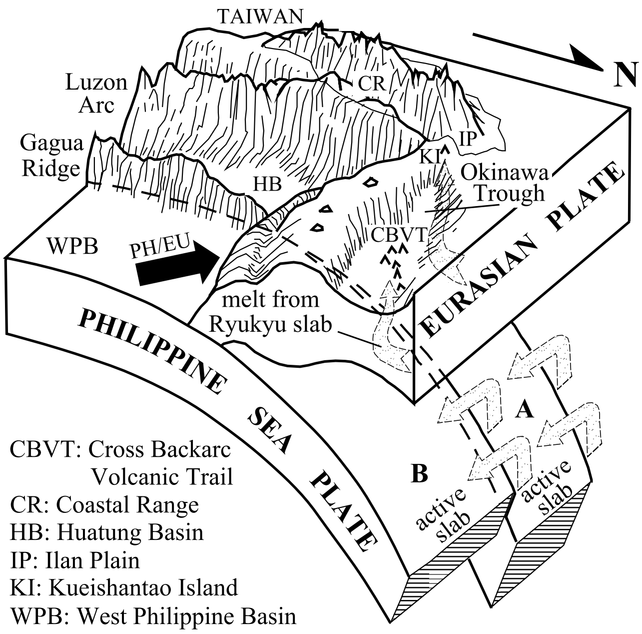

Figure 3. Diagram showing the Ryukyu slab tear occurring along the northern prolongation of Gagua Ridge, in the northwestern corner of the Philippine Sea plate. Stippled arrows indicate fluid migrating pathways around the slab edges. Contorted stippled arrows give an indication of the oblique fluid and melt pathway to the cross backarc volcanic trail (CBVT) and Kueishantao Island. Black arrow shows PH/EU plate motion.

additional amount of fluid might be released in the slab tear region, along the vertical portion of slab B located above slab A. In that case, the H_2O-rich fluid would be conveyed from around the edge of slab B in direction of the CBVT magmas. After fluid-mantle interactions and introduction of fluids into basaltic magmas, mostly produced in the uppermost mantle and lower crust, magmas would rise up along veins and conduits into the overlying upper crust of the CBVT area, accounting for the contrast of magnetization between this volcanic body and the adjacent OT crust. However, it is widely accepted that an increase of water amount in the mantle wedge results in an increase of the degree of melting and melt flux [*Stolper and Newman*, 1994]. A combination of higher water flux and melt flow in the mantle wedge, possibly driven by the geometry of the slab tear, might account for the abnormal magmatism in the CBVT region. Such a model is illustrated in the sketch of Figure 3.

[10] **Acknowledgments.** The GMT software package was used to make some of the figures [*Wessel and Smith*, 1991]. This work was carried out within the frame of the Sino-French cooperation in Geosciences. We thank the National Science Council (NSC) of Taiwan and the Institut Français à Taipei (IFT) for their financial support during the Ph. D. thesis of one of us (J.-Y. Lin). Pertinent discussions with S.-L. Chung, L. Ciron, L. Dosso, C.-S. Lee and W. Roest are acknowledged as well as a very constructive and helpful review from R. Shinjo.

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