

LETTER

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Detailed bathymetry and magnetic anomaly in the Central Ryukyu Arc, Japan: implications for a westward shift of the volcanic front after approximately 2.1 Ma

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Abstract

Detailed bathymetry and magnetic anomalies in the southern part of the Central Ryukyu Arc reveal recent volcanic structures in a southwestward extension of the active volcanic front of the Ryukyu Arc. A line of bathymetric highs running subparallel to this recent volcanic front was observed approximately 20 km to the east. A set of small, sharply defined magnetic anomalies extends southward from this line of bathymetric highs to the islands Kume-jima and Aguni-jima, suggesting the former existence of an ancient volcanic front. The ages of volcanic rocks from these islands indicate that magmatic activity along the ancient volcanic front continued until at least approximately 2.1 Ma. The presence of magnetic anomalies between the two volcanic fronts suggests that the volcanic front has moved gradually westward. This shift can be explained by the termination of asthenospheric upwelling and/or the rapid retreat of the Ryukyu Trench after its change in subduction direction.

Keywords: Ryukyu Arc; Okinawa Trough; Arc volcanism; Seafloor morphology; Magnetic anomaly

Findings

Introduction

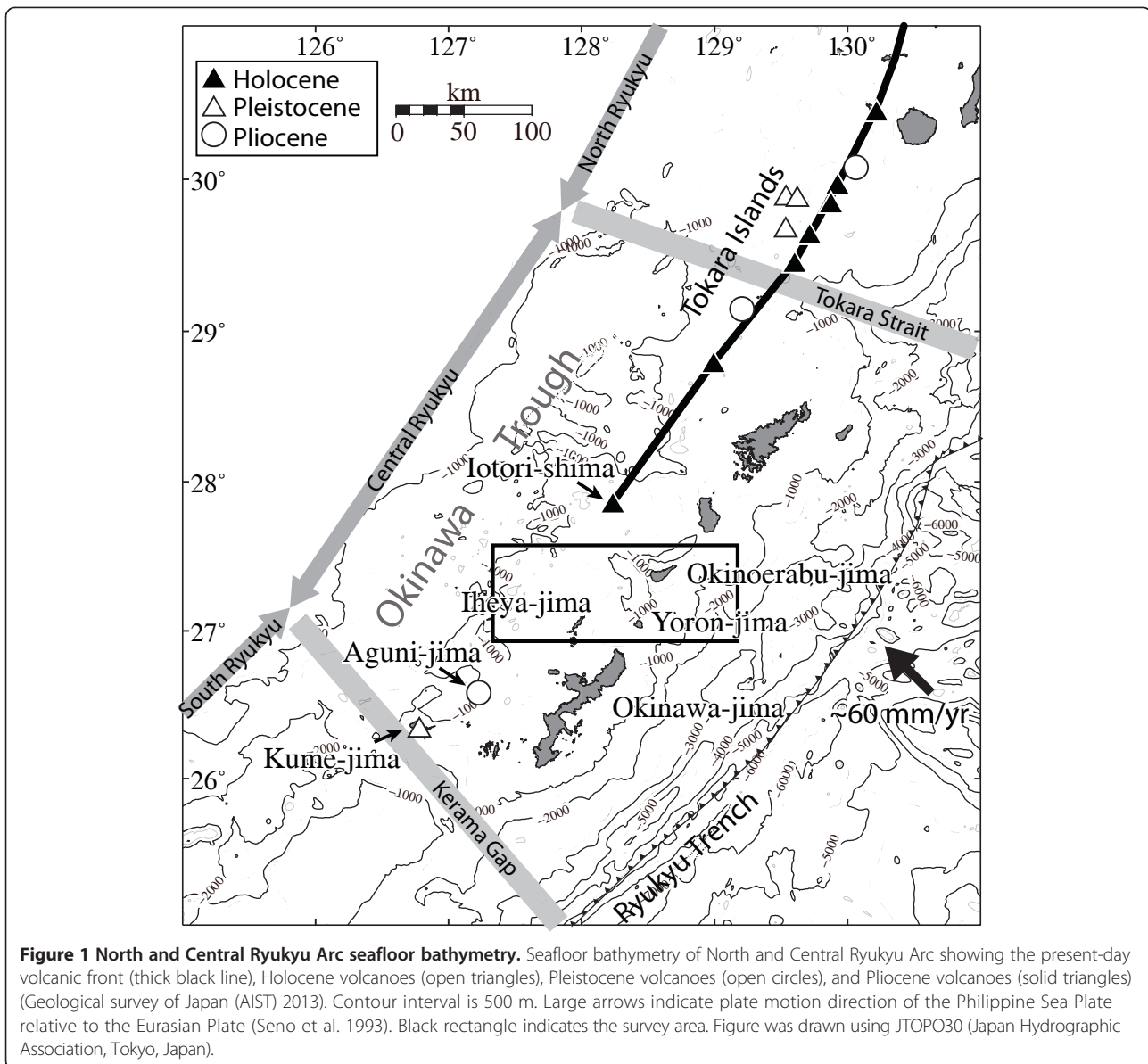
The Ryukyu Arc extends approximately 1,200 km between the islands of Kyushu and Taiwan, where the Philippine Sea Plate subducts northwestward under the Eurasian Plate. The rate of convergence across the arc increases from 40 mm/yr in the northern part of the arc to 67 to 71 mm/yr in the southern part (Seno et al. 1993). From east to west, the arc consists of the Ryukyu Trench, the Ryukyu Islands, a volcanic front, and the Okinawa Trough (Figure 1). The Ryukyu Arc is generally divided into northern, central, and southern regions bounded by the Tokara Strait and the Kerama Gap (e.g., Konishi 1965; Kato et al. 1982). The Tokara Islands are on the present-day volcanic front, which extends from Kyushu into the eastern margin of the Okinawa Trough in the Central Ryukyu Arc. Active volcanic islands do not occur to the southwest of Iotori-shima in the Central Ryukyu Arc,

although some bathymetric highs and associated magnetic anomalies have been reported (Otani et al. 2004).

The Okinawa Trough is generally interpreted as being in the early stage of rifting (e.g., Sibuet et al. 1987, 1995, 1998; Miki 1995; Shinjo et al. 1999; Fournier et al. 2001; Hsu et al. 2001; Fabbri et al. 2004; Lin et al. 2005). We have divided the Okinawa Trough into northern, central, and southern regions corresponding to the divisions of the Ryukyu Arc (Konishi 1965) (Figure 1). Active back-arc rifting accompanied by volcanic ridges and numerous volcanoes has been recognized in the Central Okinawa Trough (e.g., Sibuet et al. 1987; Oshima et al. 1988) but not in the North Okinawa Trough. Geochemical research has suggested that enriched mid-ocean ridge basalt (E-MORB)-type upwelling of the asthenospheric mantle and a subduction component have been involved in the generation of basalt in the Central Okinawa Trough (Shinjo et al. 1999). This implies that the magmatic activity of the volcanic front and back-arc overlap in the Central Okinawa Trough.

However, whether the volcanic front to the southwest of Iotori-shima existed in the past is unknown, and the cause of the possible overlap of the two types of

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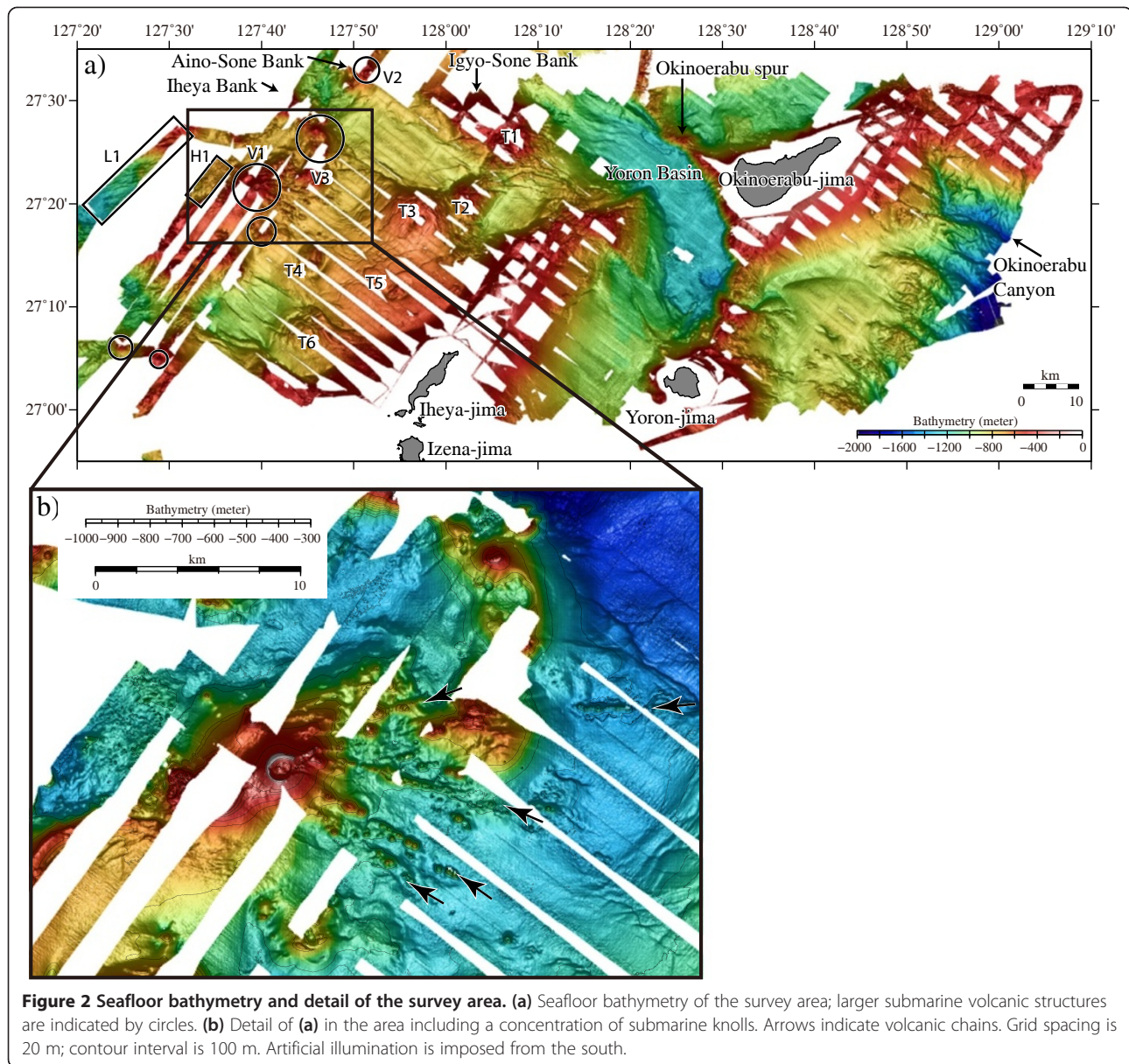
magmatic activity in the Central Ryukyu Arc is not clear. Clarifying the temporal and spatial variabilities of magmatic activity in the volcanic front and back-arc region will contribute to the understanding of the early rifting process of this region.

To address these issues, we conducted a detailed geophysical survey by using bathymetry, gravity and magnetics in the Central Ryukyu Arc around the islands of Yoron-jima, Okinoerabu-jima, and Iheya-jima (Figure 2). Such geophysical surveys are known to be useful in delineating submarine volcanic features (e.g., Kim et al. 2013). This survey was performed in 2012 during the Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology (AIST), GH12 cruise of R/V *Hakurei*.

Geophysical data acquisition and processing

Bathymetric data were collected with a multi-beam echo sounding system (EM122, Kongsberg Maritime AS, Kongsberg, Norway) composed of 432 beams with an operating frequency of 12 kHz. The sound velocity correction used real-time data from the surface water velocity meter and the sound velocity profiles collected by conductivity, temperature, and depth (CTD), expendable CTD (XCTD), and expendable bathythermograph (XBT) observations in the study area. We used HIPS and SIPS software (CARIS, Ltd., Fredericton, Canada) to remove extreme depth variations from the outer edges of the multibeam swaths.

Total magnetic field data were acquired at 1-s intervals with a surface-towed cesium magnetometer (G-882,



Geometrics, Inc., San Jose, CA, USA). The sensor was towed 240 m behind the ship to minimize the ship's magnetization effect. Magnetic anomalies were calculated by subtracting the 11th generation International Geomagnetic Reference Field (Finlay et al. 2010) from the observed magnetic field intensity. Magnetic diurnal variation was corrected using data from the Gesashi magnetic observatory on Okinawa-jima operated by the Geospatial Information Authority of Japan. Crossover error assumed to be mainly caused by the ship's magnetization was minimized by using the software package x2sys of Generic Mapping Tools (GMT) (Wessel 2010; Bullard and Mason 1961). These corrections reduced the standard deviation at crossover points from 12.2 to 5.1 nT. Finally, the reduced-to-pole magnetic

anomaly was calculated using Mirone software (Luis 2007). The direction of seafloor magnetization was assumed to be the same as that of the geocentric axial dipole field of the study area.

Results

Bathymetry

The survey area is in the middle of the Central Ryukyu Arc around the islands of Yoron-jima, Okinoerabu-jima, and Iheya-jima (Figure 2a). The water depth in the survey area is between 500 and 1,200 m. Yoron-jima and Okinoerabu-jima are non-volcanic islands connected by a NE-SW-trending shallow ridge. Several well-developed submarine canyons, such as Okinoerabu Canyon, cut into the upper fore-arc slope east of the islands of the

Ryukyu Arc. A basin approximately 1,200 m deep, the Yorou Basin, lies west of Okinoerabu-jima. Northeast of Iheya-jima, a NE-SW-trending ridge 400 to 500 m high rises at a depth of approximately 1,000 m. About 60 km north of Iheya-jima, the Igyo-Sone Bank lies at a depth of approximately 500 m. Southwest of this bank, several isolated knolls rise approximately 100 to 300 m above the seafloor at depths of 500 to 600 m. These features are numbered T1 to T6 in Figure 2a.

In the westernmost part of the survey area, several submarine knolls as large as 8 km in diameter are observed. Because some of them have craters, they are interpreted as submarine volcanoes. The largest one with a crater, at 27° 22' N, 127° 39' E, is approximately 500 m high (Figure 2b). Just west of these volcanoes, hummocky terrain (H1 in Figure 2a) similar to those often found in the axial areas of mid-ocean ridges (e.g., Lawson et al. 1996) is observed. Many small conical structures less than 1 km in diameter are also observed in this area (Figure 2b). Some of them have summit craters, and others are aligned in chains with orientations between ENE-WSW and SE-NW (arrows in Figure 2b); all are interpreted as volcanic origin. Farther to the west, ENE-WSW-trending lineaments (L1 in Figure 2a) are interpreted as being caused by normal faults associated with rifting in the Okinawa Trough.

Magnetics

Reduced-to-pole magnetic anomalies vary between -110 and 640 nT (Figure 3a). East of the Ryukyu Arc, the anomaly varies between -20 and 60 nT and is relatively featureless. However, five well-defined positive magnetic anomalies are observed in a line extending southwest from the southern end of Igyo-Sone Bank (M1 to M5 in Figure 3a). The largest of these, reaching 640 nT (M1), corresponds to the southern part of the Igyo-Sone Bank. Some of these positive anomalies are associated with knolls. A weak positive anomaly is observed over the small submarine volcanoes and volcanic chains west of anomaly M4 (Figures 2b and 3a). Positive anomalies as large as 120 nT are observed over the two largest volcanic knolls (V1 and V2). The area of hummocky terrain (H1 in Figure 3a) is associated with a negative anomaly.

Discussion

Recent volcanic front

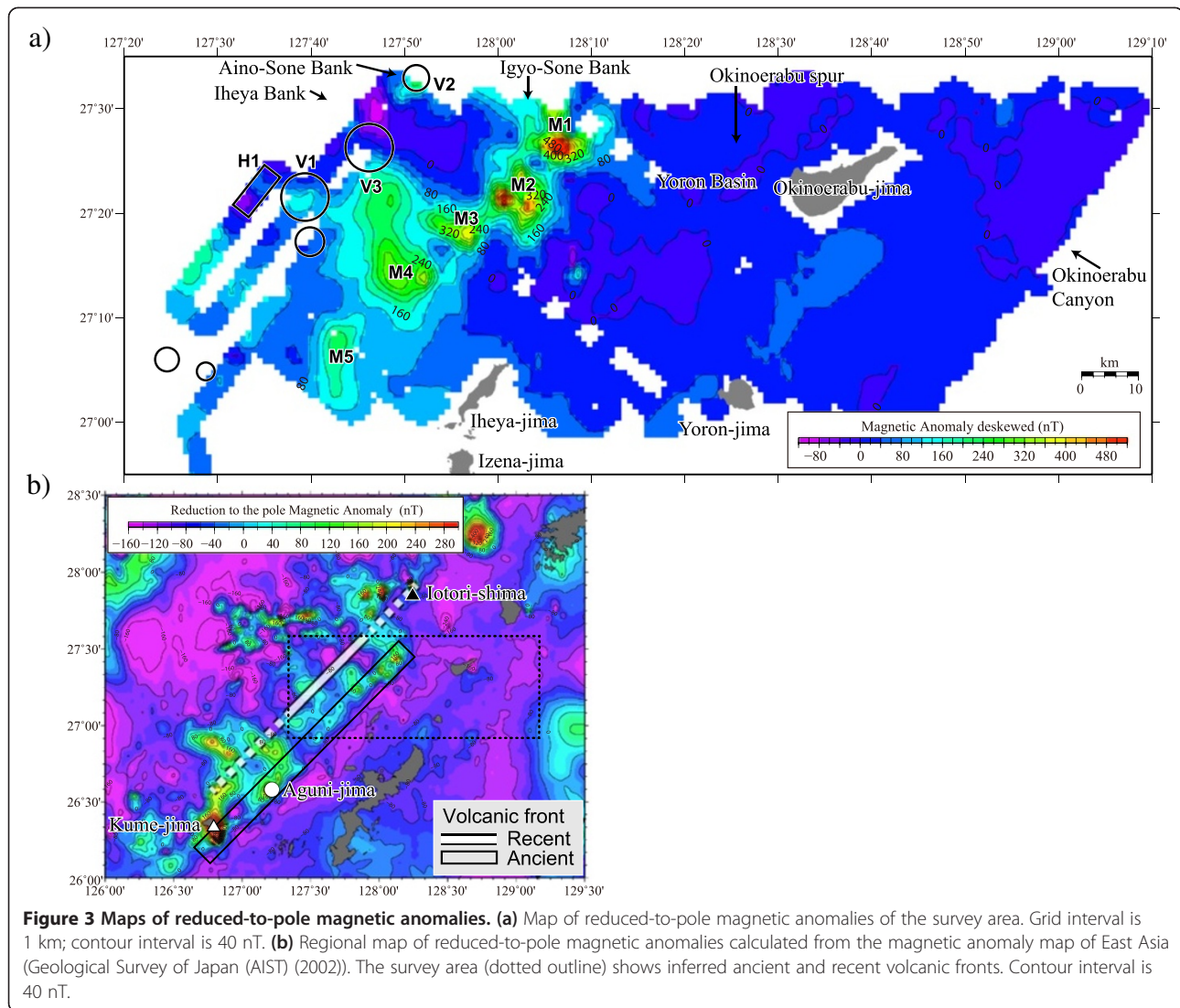
The volcanic front in the Central Ryukyu Arc has been delineated by previous studies (e.g., Sibuet et al. 1998). Geochemical data from submarine volcanoes and several volcanic chains have been documented in the northern part of this segment (Yokose et al. 2010). However, magmatic activities in the southern part are less well known, despite the presence of magnetic anomalies associated with topographic highs (Geological Survey of Japan (AIST)

(2002); Otani et al. 2004) and the discovery of pumice approximately 300 m deep in a bank at 27° 17' N, 127° 29' E (Otani et al. 2004). Many submarine volcanic structures observed in the western part of the survey area are generally aligned in a NE-SW direction (Figure 2a) in the south-westward extension of the present-day volcanic front at the Tokara Islands (Figure 1). This suggests that the volcanic front once extended into the southern part of the Central Ryukyu Arc. Therefore, we recognized this line of volcanoes as a recently active part of the volcanic front. The two largest submarine volcanic knolls (V1 and V2 in Figure 2) have clear positive magnetic anomalies larger than 100 nT (Figure 3a), implying that they were active volcanoes during a normal-polarity chron or short-term normal events during a reversed-polarity chron. In addition, a positive magnetic anomaly was observed over the chains of small volcanic knolls (arrows in Figure 2b), suggesting the presence of igneous rocks beneath the seafloor, which may correspond to magmatic bodies of ancient volcanoes (Figures 2b and 3a). These small volcanic knolls belong to the V-series, and the orientations of these chains appear to be related to previous tectonic extensions (Fournier et al. 2001).

Ancient volcanic front

We observed a line of positive magnetic anomalies oriented NE-SW in the middle of the survey area (M1 to M5 in Figure 3a), which is subparallel to the present and recent volcanic fronts and approximately 20 km east of the recent volcanic front. Bathymetric and seismic surveys during the GH12 cruises (Sato et al. 2013) showed that these anomalies coincide with knolls (M1 to M3 and M5) and a buried basement high (M4) that display no evident volcanic structures, suggesting sediment cover and weathering. This chain of magnetic anomalies is a part of a larger magnetic feature observed in the southern half of the Central Ryukyu Arc (Geological Survey of Japan (AIST) (2002)) (Figure 3b). Therefore, we interpreted the chain to be a part of an ancient volcanic front.

Kume-jima and Aguni-jima islands to the south of this feature are associated with notable positive magnetic anomalies (Figure 3b). Kume-jima has two recognized volcanic formations, the Aradake Formation of Miocene age and the Uegusukudake Formation of Pliocene age (Nakagawa and Murakami 1975). Andesites from the Aradake Formation show fission-track ages of 15.1 ± 2.6 Ma and 12.8 ± 2.1 Ma (Daishi et al. 1987). Volcanic rocks in the Uegusukudake Formation show K-Ar dates of 2.76 ± 0.48 Ma from picrite basalt in the lowest part (Ito and Shiraki 1999), 2.24 ± 0.10 Ma from andesite in the upper part (Miki 1995), and 2.13 ± 0.19 Ma from basaltic andesite lava in the middle part (Kitagawa and Shinjo 2001). A Pliocene high-Mg andesite from O-jima, just east of Kume-jima, shows a K-Ar date of 6.08 ± 0.46 Ma (Shinjo



et al. 1991). On Aguni-jima, the age of the volcanic Aguni Formation is between the late Miocene and early Pliocene (Kizaki 1986). Dacite of the Aguni Formation shows a fission-track date of 6.24 ± 0.46 Ma (Daishi et al. 1987).

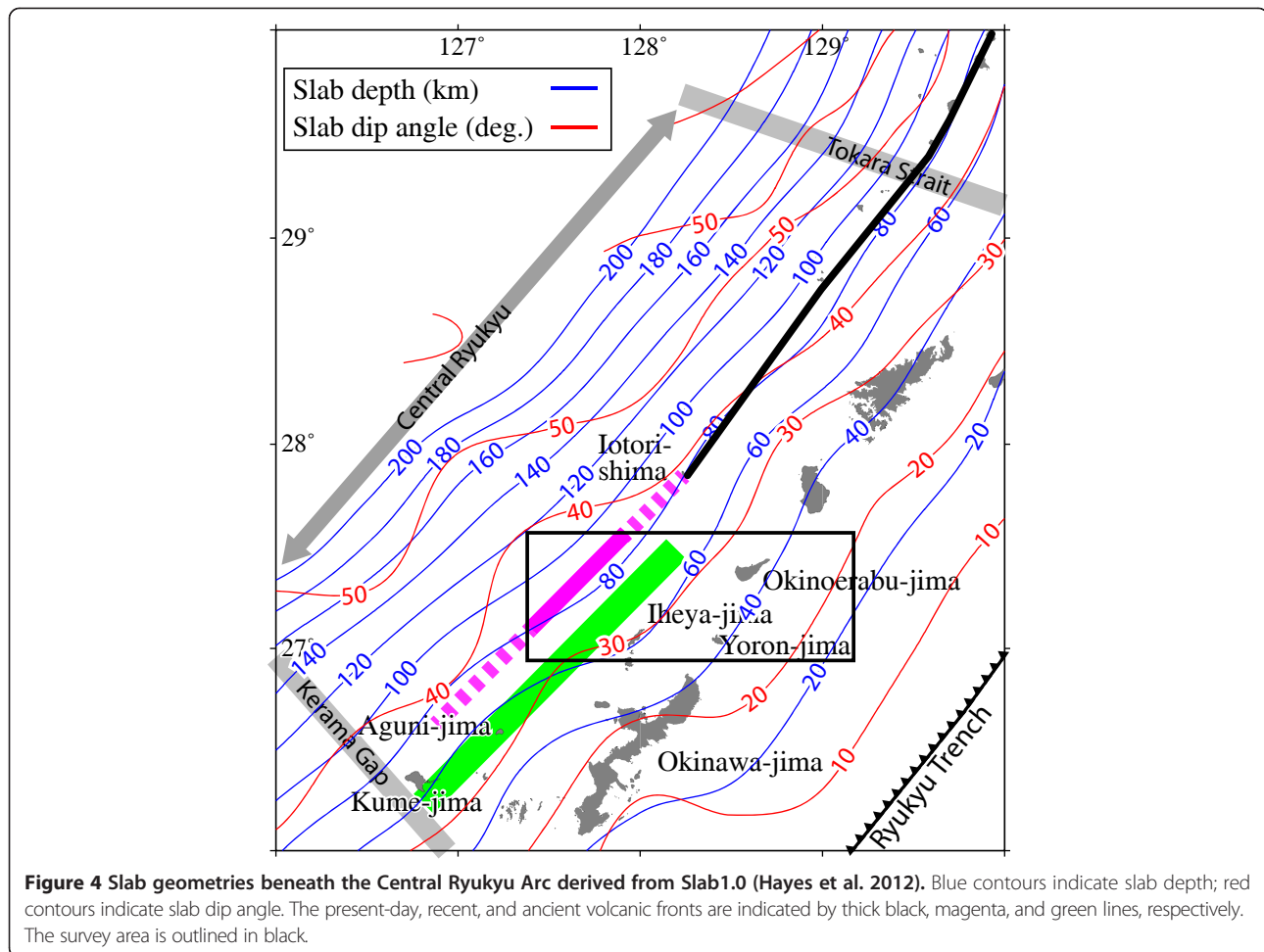
These dated rocks suggest that magmatic activity in the southern half of the Central Ryukyu Arc continued until around approximately 2.1 Ma, and high-Mg rocks were produced as late as approximately 2.3 Ma. Although we have no radiometric ages for the rocks associated with the magnetic anomalies M1-M5 (Figure 3a), the association of the anomalies with dated volcanic rocks in the southern half of the Central Ryukyu Arc (Figure 3b) suggests that magmatic activity persisted in the survey area into early Pleistocene time.

Shift of volcanic front toward the back-arc region

No notable magnetic anomalies or topographic features indicative of volcanic structures are found east of the ancient

volcanic front (Figure 3b). This finding, together with the presence of small magnetic anomalies between the recent and ancient volcanic fronts, suggests that the volcanic front has moved gradually to the west (Figure 3a,b).

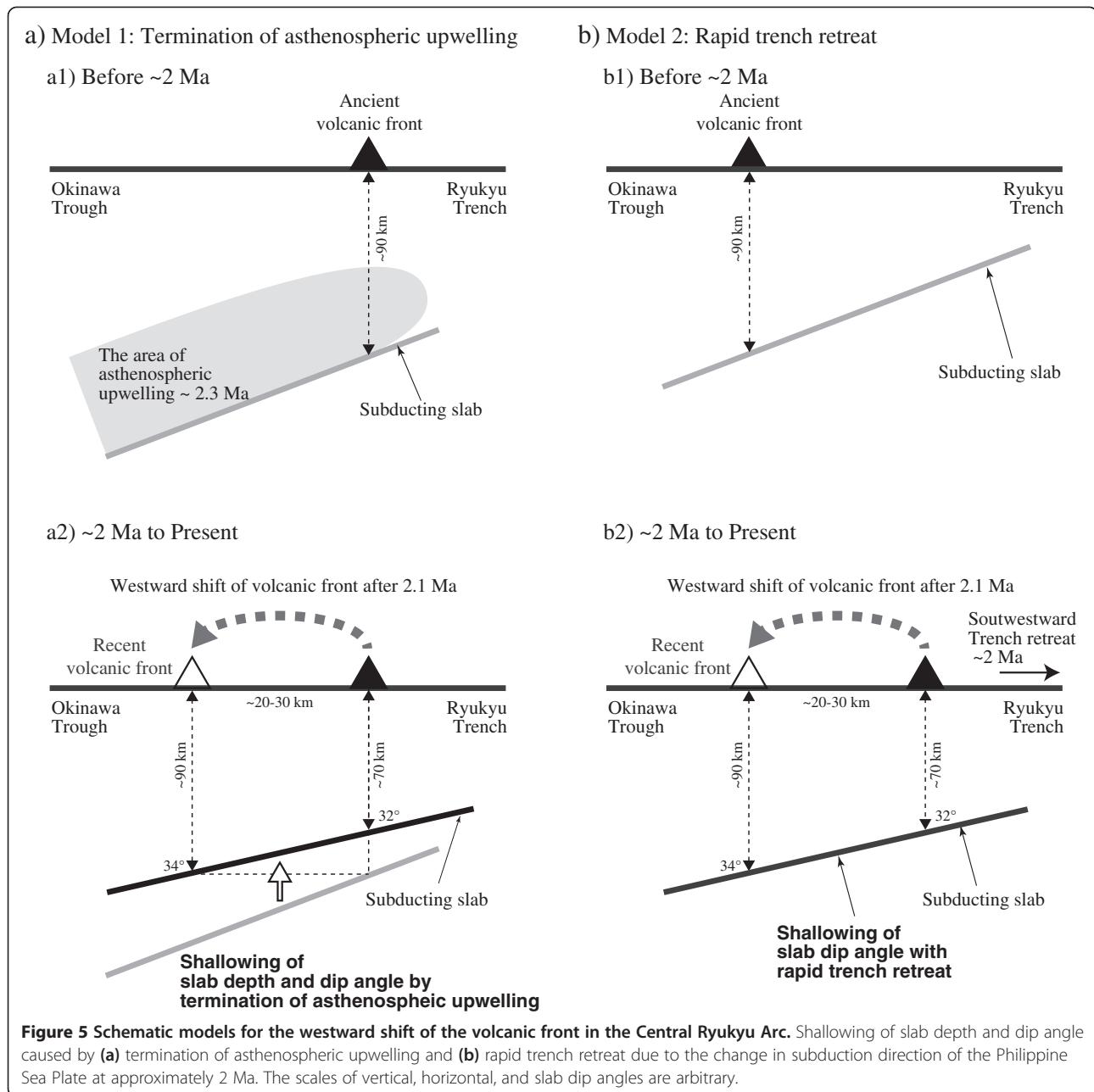
According to the slab model of Hayes et al. (2012), the slab depths are 80 to 90 km beneath both the active volcanic front of the Ryukyu Arc around the Tokara Islands in the North Ryukyu Arc and the recent volcanic front identified in this study (Figure 4). These slab depths are also consistent with the established concept that the position of the volcanic front is governed by dehydration of the subducting plate (e.g., Tatsumi 1986; Kogiso et al. 2009). The current slab depth beneath the ancient volcanic front is approximately 70 km, which is shallower than that beneath the recent and present volcanic fronts (Figure 4). Assuming that the slab depth was deeper when the ancient volcanic front was active, the subsequent westward shift of the volcanic front would



have been accompanied by shallowing of the slab beneath it (Figure 5). We propose two possible explanations for this change in the subduction geometry: termination of asthenospheric upwelling beneath the southern part of the Central Ryukyu Arc (Figure 5a) and rapid trench retreat due to a change in the subduction direction of the Philippine Sea Plate (Figure 5b).

The first hypothesis is based on the model proposed by Shinjo (1999). Relatively primitive basalt and high-Mg andesites of middle to late Miocene age have been found in the Central and South Ryukyu Arc (e.g., Shinjo 1999). For example, adakitic high-Mg andesites from the Central Ryukyu Arc show the clear geochemical signature of a slab-derived component from the slab melt (Shinjo 1999). Although many adakites were produced during the subduction of young, hot oceanic crust of less than 25 Ma (Defant and Drummond 1990), the subducting Philippine Sea Plate beneath the Central Ryukyu Arc consists of relatively old oceanic crust of approximately 54 to approximately 26 Ma (Deschamps and Lallemand 2002). Therefore, asthenospheric upwelling is postulated to have produced the adakitic high-Mg andesite (Shinjo

1999). The ages of the picrite basalt (Ito and Shiraki 1999) suggest that asthenospheric upwelling continued until no later than approximately 2.3 Ma (a1 in Figure 5a). Asthenospheric upwelling can affect the depth and dip angle of the slab by changing the thermal state or mantle flow beneath the volcanic front. Currently, the slab dip angle differs between the North and Central Ryukyu Arc (e.g., Shiono et al. 1980; Christova 2004). According to the slab model of Hayes et al. (2012), there is a distinct difference (approximately 5 to 10°) in the slab dip angle beneath the volcanic front in the Tokara Islands in North Ryukyu Arc and that beneath the submarine volcanoes in the Central Ryukyu Arc identified in this study (Figure 4). This difference in the slab dip is attributed to a difference in shear resistance to the subduction (e.g., Shiono et al. 1980; Kao and Chen 1991; Christova 2004); when resistance is greater, a slab is subjected to more compressional stress and has a shallower dip. Alternatively, the slab dip angle is attributed to the degree of pressure force generated by mantle flow (e.g., Heuret and Lallemand 2005); weakening the mantle flow pushing on the upper plate side of the



slab creates a shallower slab dip angle. Based on the previous geochemical studies, we suggest that the contribution of asthenospheric upwelling to volcanism in the ancient arc ended at approximately 2.3 Ma. This change may have decreased the mantle temperature to result in an increase in the resistance to subduction; alternatively, it may have weakened the asthenospheric mantle flow to result in a decrease in pressure. Both mechanisms can lead to shallowing of the slab depth and dip angle (a2 in Figure 5a). The second hypothesis is inferred from the rapid trench retreat of the Ryukyu Arc proposed by Kamata and Kodama (1999).

The change in the subduction direction of the Philippine Sea Plate from N-NW to NW occurred at approximately 2 Ma, and oblique subduction has replaced the arc-normal subduction at the Central Ryukyu Arc, resulting in a more rapid southeastward retreat of the Ryukyu Trench (Kamata and Kodama 1999). Assuming that the initial slab dip angle was steeper than its current position (b1 in Figure 5b), and if the slab was anchored in the mantle and its dip shallowed with the trench retreat, westward migration of the volcanic front is likely (b2 in Figure 5b). To clarify the timing of the shift of the volcanic front and to assess our proposed

models, integrated geological and geophysical surveys from the ancient to the recent volcanic front, including deep drilling, are necessary.

Conclusions

A geophysical survey in the southern part of the Central Ryukyu Arc revealed detailed bathymetry and magnetic anomalies, which were then interpreted in combination with regional magnetic data. The following conclusions are drawn:

- (1) A recently active volcanic front of the Ryukyu Arc occurs along the southwestward extension of the present-day volcanic front, according to conical topographic structures that are interpreted as submarine volcanoes.
- (2) Well-defined magnetic anomalies associated with basement topographic highs suggest the presence of an ancient volcanic front that is subparallel to and approximately 20 km east of the recent volcanic front. Being as Kume-jima and Aguni-jima would be a part of the ancient volcanic front, the ages of the volcanic activity at these islands indicate that the ancient volcanic front may have been active until approximately 2.1 Ma.
- (3) The geometry and magnetic features of these two volcanic fronts suggest a gradual westward shift of the southern part of the Central Ryukyu arc's volcanic front in Quaternary time. We offer two candidate mechanisms for this shift. The first is shallowing of the slab depth and dip angle induced by the termination of asthenospheric upwelling beneath the southern part of the Central Ryukyu Arc. The second is rapid southeastward retreat of the Ryukyu Trench approximately 2 Ma.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

TS, HO, and KO conducted the geophysical survey. TS and HO processed the data. All contributed to discussion, and TS, HO, OI, and KO wrote the manuscript. All authors read and approved the final manuscript.

Acknowledgements

The data used in this study were obtained by the Geological Survey of Japan of National Institute of Advanced Industrial Science and Technology (AIST), conducted as part of the marine geological survey of the region around Okinawa. We thank the captain and crews of *R/V Hakurei* and the GH12 cruise science party for their help in collecting data and for offering valuable advice.

Received: 24 February 2014 Accepted: 30 June 2014

Published: 7 July 2014

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doi:10.1186/1880-5981-66-68

Cite this article as: Sato *et al.*: Detailed bathymetry and magnetic anomaly in the Central Ryukyu Arc, Japan: implications for a westward shift of the volcanic front after approximately 2.1 Ma. *Earth, Planets and Space* 2014 **66**:68.

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