High-resolution aeromagnetic anomaly map of the Vulcano-Lipari volcanic complex, Aeolian Islands, Italy

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Abstract: Two high-resolution aeromagnetic surveys three years apart were conducted to better understand the shallow subsurface structure of the Vulcano and Lipari volcanic complex, Aeolian Islands, southern Italy and monitor the volcanic activity of the area. The surveys were flown by helicopter at a mean altitude of 150 m above the terrain with NW-SE flight lines spaced about 250 m apart. In this kind of survey, however, the actual flight altitude varies, and the reduction of observed data to a smoothed surface is required to represent accurate magnetic anomalies. The equivalent source technique was employed for this purpose.

A comparison between datasets at two different times was conducted to monitor the volcanic activity of the area. The subtraction of the 1999 data from the 2002 data indicates high-frequency residuals especially in magnetically high-gradient areas on Vulcano. The differences were caused probably by spatial aliasing because of insufficient survey line spacing for these areas and by altitude error based on different positioning methods. These conditions imply that it is difficult to judge if there were meaningful changes related to volcanic activity between the two surveys. Therefore, we proceeded to compile a magnetic anomaly map based mainly on the 2002 survey data with the inclusion of some profiles from the 1999 survey to cover a larger area than the individual surveys.

Total magnetic intensity anomalies on the common surface parallel to and 150 m above the smoothed terrain and sea surface were complied. The map clearly shows that high-frequency and high-amplitude magnetic anomalies are distributed mainly on Vulcano, suggesting surface and shallow subsurface distributions of mafic volcanic rocks. On the other hand, no apparent magnetic anomalies lie on the southern Lipari, indicating that the area is composed of more felsic volcanic rocks than Vulcano.

Furthermore, apparent magnetization intensity mapping was applied to terrain-corrected magnetic anomalies, and a reduction to the pole anomaly map was also calculated at the same time. By comparison with a geologic map, the reduction to the pole anomaly map showed local magnetic highs in the Piano district, southern Vulcano, corresponding to some outcrops of trachybasaltic-trachyandesitic rocks which fill up Piano Caldera and lie on the flanks of Primordial Vulcano (South Vulcano). Magnetic highs are also distributed in and around Fossa Cone, northern Vulcano, corresponding to trachytic and tephritic lavas forming the cone. Local magnetic highs lie on the northern (Forgia Vecchia) and eastern slopes of the cone without surface signatures. According to the result of magnetic modeling on these magnetic highs (Okuma *et al.*, 2006), past volcanic centers that produced thick lava accumulations in Fossa Crater are implied to be overlain by thick pyroclastic rocks in these areas.

This paper focuses on the compilation of an aeromagnetic anomaly map of the study area.

Keywords: high-resolution aeromagnetic survey, magnetic map, Vulcano, Lipari, Aeolian Islands, volcanic hazard mitigation, reduction to the pole, magnetization

1. Introduction

The Aeolian Island arc is located in the Tyrrhenian Sea, southern Italy and composed of seven volcanic islands: i.e. Alicudi, Filicudi, Salina, Lipari, Vulcano, Panarea and Stromboli from west to east (Fig. 1). The volcanic activity of the islands is thought to originate from the subduction of the African plate beneath the European plate at the southern edge of the Tyrrhenian Sea (Furukawa *et al.*, 2001). Since ancient Greek times, Stromboli in particular has been noted for its effusive eruptions mainly of lava products, and Vulcano was

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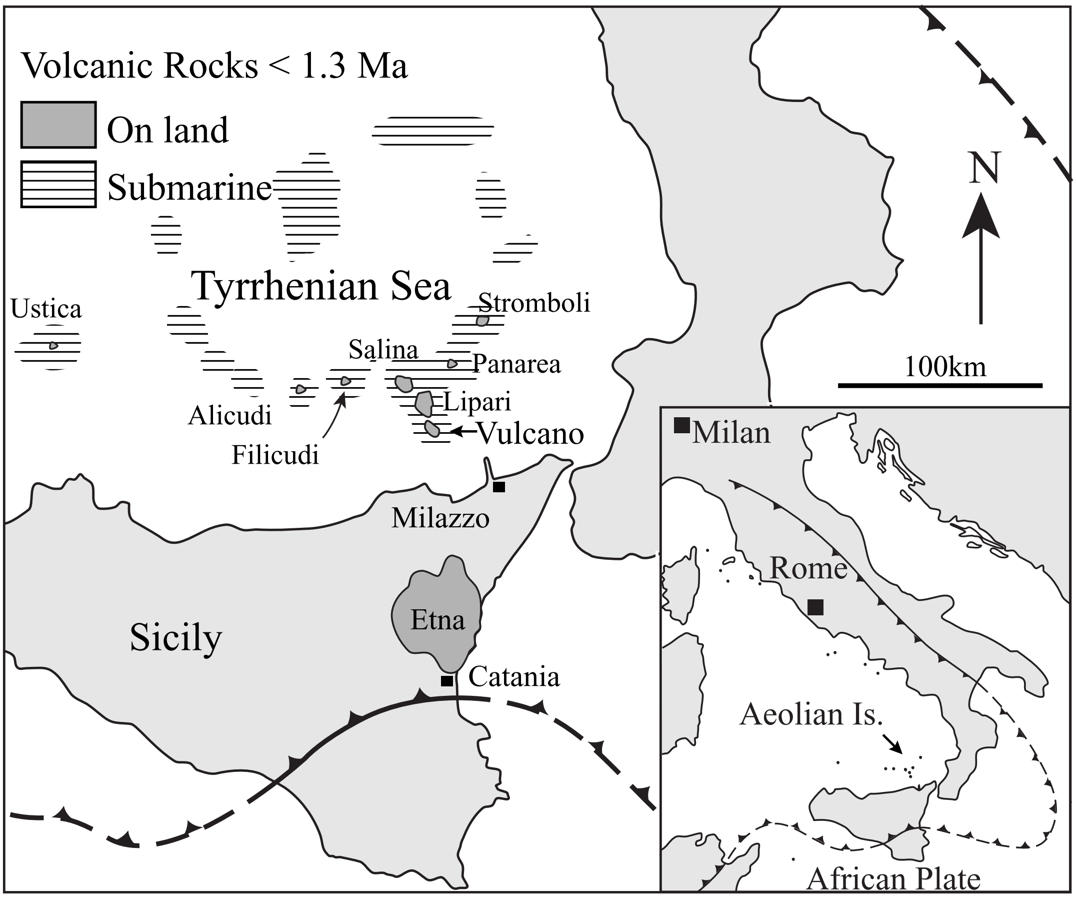

Fig. 1 Study area. The map shows the Aeolian Islands located between Sicily and the southern tip of the Italian Peninsula in the Tyrrhenian Sea. It also indicates the distribution of volcanic rocks of the age younger than an 1.3 Ma (after Furukawa *et al.*, 2001).

noted for its violent "Vulcanian" eruptions that emitted large quantities of volcanic bombs and ash.

The activity at Vulcano (Fig. 2) has been unusually quiet since the last eruption took place between 1880-1890. This relatively long period of inactivity has caused concern that a future eruption could be explosive and cause severe damage. To predict future eruptions and mitigate their hazards, it is important to know the subsurface structure of the volcano in detail as well as to monitor its activity.

Since 1999, the Geological Survey of Japan and Geological Survey of Austria (GBA) have been conducting geophysical surveys and studied the repeated geophysical measurements on the Aeolian Islands, Italy to mitigate the volcanic hazard of the area (Okuma *et al.*, 2001). Regional gravity surveys with the cooperation of GBA were initiated in 2000 on the Vulcano and Lipari Islands, and a high-resolution gravity survey was also conducted along the slopes of Fossa Cone, Vulcano (Komazawa *et al.*, 2002; Sugihara *et al.*, 2002).

In 2001, the Institute of Geology and Geoinformation (previously Institute of Geoscience), National Institute of Advanced Industrial Science and Technology (AIST) and the GBA signed a cooperation agreement to promote geophysical studies on geologic hazard mitigations especially in a volcanic environment. AIST and GBA conducted a high-resolution aeromagnetic survey to better understand the shallow subsurface structure of the Vulcano and Lipari complex (Fig. 3) and monitor the volcanic activity of the area in 2002, three years after the initial survey (Supper *et al.*, 2001, 2004; Okuma *et al.*, 2003).

2. Geological Settings

The Vulcano and Lipari volcanic complex belongs to the Aeolian volcanic island arc and its general geology (Fig. 4; Okuma *et al.*, 2006) is explained briefly below.

2.1 Vulcano

Vulcano consists of four major volcanic structures whose activity developed between 120 ka and histori-

Fig. 2 La Fossa Cone, Vulcano volcano with an altitude of 391 m ASL viewed from the eastern offshore. A landslide that occurred in 1988 can be seen slightly right of the center of the picture. The ridge on the left is the remains of South Vulcano (Primordial Vulcano).

cal times (Ventura, 1994). The southernmost and oldest (120-100 ka; Keller, 1980) structure is a shoshonitic stratovolcano called Primordial Vulcano (South Vulcano) (Fig. 4). At around 100 ka, the upper part of this stratovolcano collapsed and formed a caldera (Piano Caldera) about 2.5 km in diameter. Piano Caldera was filled up with tephritic and trachybasaltic lavas, and their pyroclastic deposits by later volcanic activity. About 24 ka ago, the Lentia volcanic complex was formed by rhyolitic lava with subordinated latic and trachytic lavas north of South Vulcano (De Astis *et al.*, 1997). After 15 ka, the collapse of the complex occurred and Fossa Caldera was formed. In the collapsed area, Fossa Cone, a pyroclastic cone with subordinate lava flows, trachytic and rhyolitic in composition, developed in the last 6,000 years. In the mean time, the leucite-tephritic activity of Vulcanello occurred at sea north of Fossa Caldera and formed a lava platform covered with pyroclastic deposits (Keller, 1980).

2.2 Lipari

Volcanic activity at Lipari started at around 220 ka (Crisci *et al.*, 1991) with andesitic products on the western coast (Pichler, 1980). The activity of Mt. Saint Angelo volcano in the center of Lipari lasted until 92 ka (Crisci *et al.*, 1991). After a long quiet period, the activity resumed at about 42 ka on the southern part of the island with rhyolitic lava domes and pyroclastic deposits (Gioncada *et al.*, 2003). After 23.5 ka, the activity yielded rhyolitic fall and surge deposits followed by the extrusion of lava domes (Mts. Guardia and Giardina; Crisci *et al.*, 1991). In the same phase of Mts. Guardia and Giardina, the rhyolitic domes (Castello and San Nicola) were formed on the south-eastern side of the island. The most recent volcanic activity on Lipari moved northward (Sheridan *et al.*, 1987). The rhyolitic eruptions occurred from vents aligned along a N-S direction on the east coast and produced pyroclastic deposits and obsidian lava flows (Gioncada *et al.*, 2003). The latest phase ended with the formation of the pyroclastic deposits and lava flow of the Forgia Vecchia and a pumice cone (Mt. Pilato) with an obsidian flow (Rocche Rosse).

3. High-resolution Aeromagnetic Surveys

A helicopter-borne high-resolution aeromagnetic survey was conducted over Vulcano and southern part of Lipari in 2002 (Okuma *et al.*, 2003; Supper *et al.*, 2004) as the second survey of this kind in this area. The survey was flown with a real-time DGPS satellite navigation system along NW-SE flight lines at a mean altitude of about 150 m above terrain and spaced 250 m apart (Table 1). The magnetic sensor in a bird was suspended 30 m below the survey helicopter.

Magnetic data was measured using a Cesium mag-

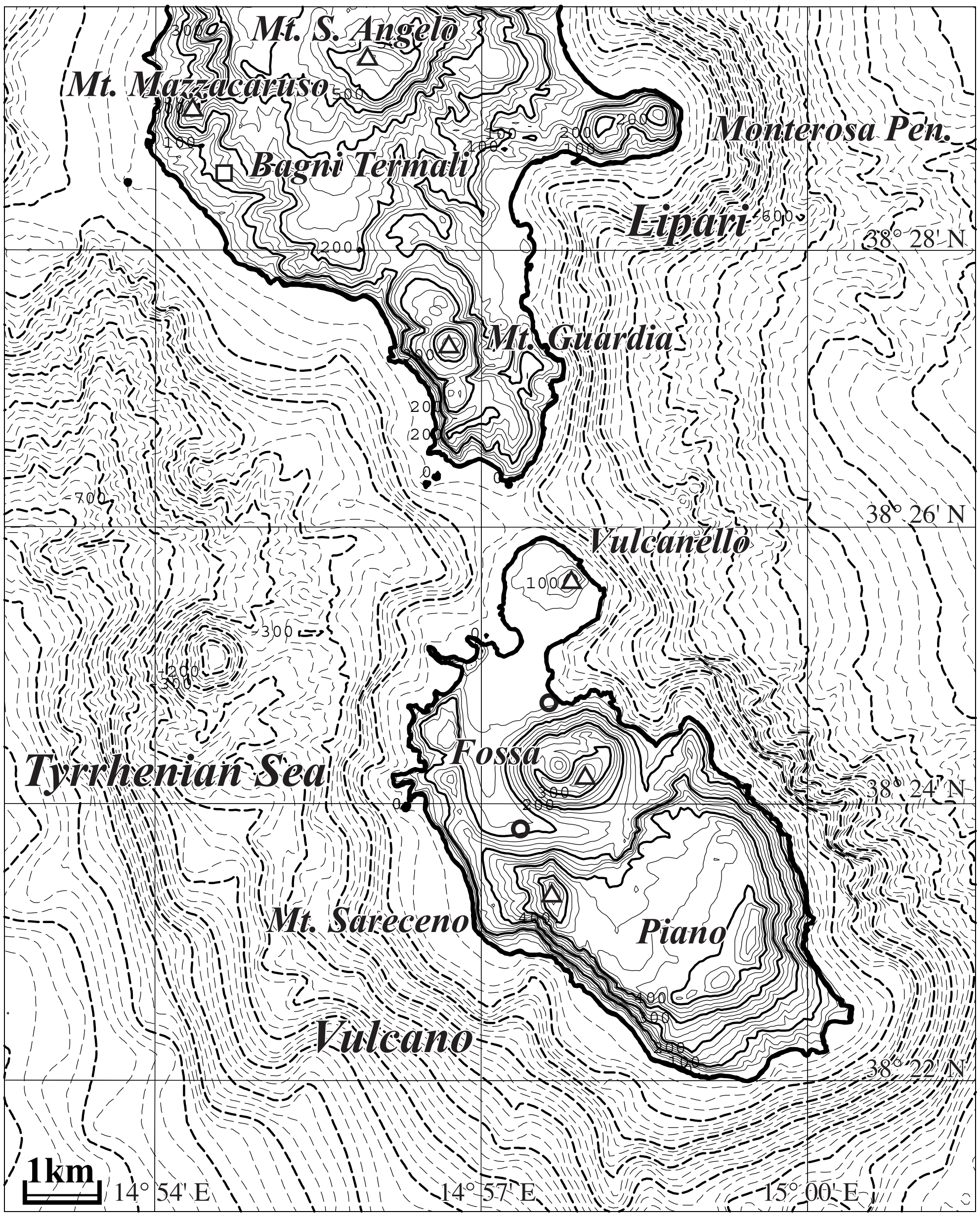

Fig. 3 Topographic map of Vulcano and Southern Lipari, drawn from the 10 m DEM (Gwinner *et al.*, 2000) and a digitized marine chart (Istituto Idrografico Della Marina, 1999). Contour interval is 25 m. Solid and broken contours indicate positive and negative values, respectively. Open circles indicate the locations of deep geothermal exploration wells.

netometer at a sampling rate of 10 Hz and with a resolution of 0.01 nT or better. The locations (latitude, longitude and altitude) of flight line path were determined using a real-time DGPS. The helicopter (Fig. 5) was also equipped with an infrared video camera to measure the surface thermal signature related to volcanic activity. During the survey period, diurnal magnetic variation was observed at the temporal base station at the heliport on Vulcanello Peninsula.

This survey was flown three years after the first survey in 1999 along almost the same flight lines as those of the previous survey. In the 1999 survey, horizontal locations of the flight line path were recovered by GPS/GLONASS satellite navigation data while terrain clearance was determined using a laser altimeter. Other survey apparatus was basically the same as that of the 2002 survey.

4. Comparison between the 1999 and 2002 survey data and compilation of magnetic anomalies

Observed data of the 2002 survey were processed deep geothermal exploration wells.

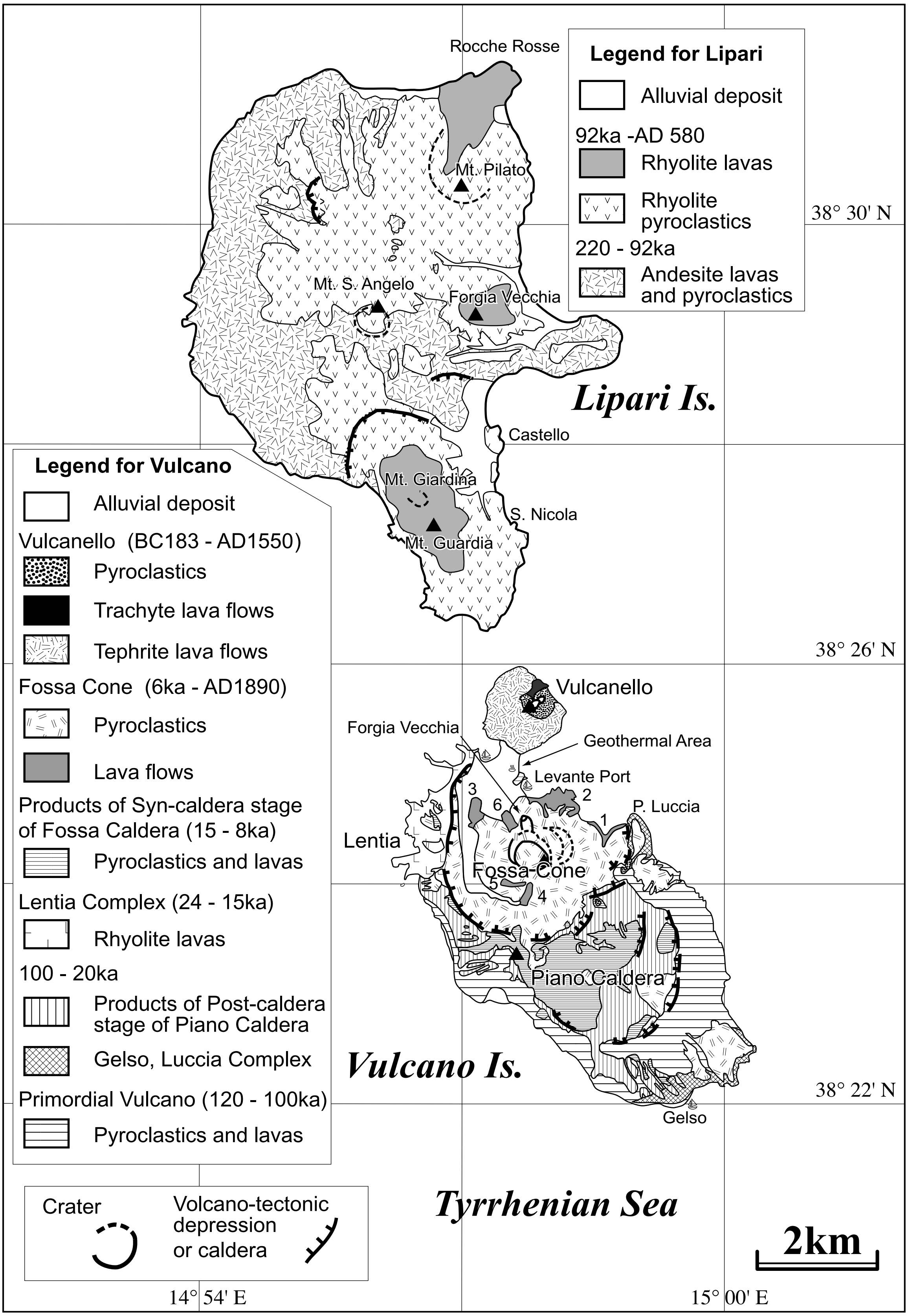

Fig. 4 Simplified geological map of the Vulcano and Lipari Islands, Italy (Okuma *et al.*, 2006). Numbers from 1 to 6 on Vulcano correspond to lava flows — 1: Punta Roia (Tephrite), 2: Punte Nere (Trachyte), 3: Campo Sportivo (Trachyte), 4: Palizzi (Trachyte), 5: Commenda (Rhyolitic Obsidian), 6: Pietre Cotte (Rhyolitic Obsidian).

Table 1 Outline of the high-resolution aeromagnetic survey over the Vulcano-Lipari volcanic complex conducted in 2002.

Survey period	November 3 - November 6, 2002
Survey area	Refer to Fig. 3
Survey helicopter	Aerospatiale AS350 B2
Flight altitude	150 m above terrain
Flight lines	Total 290 km, in NW-SE direction, 250 m spacing
Navigation / Flight path recovery	Visual flight aided by GPS positioning / Real-time DGPS
Air base	Heliport at Vulcanello, Vulcano, Aeolian Islands, Italy
Ground station	Heliport at Vulcanello, Vulcano, Aeolian Islands, Italy 38°25'40" N, 14°57'20" E (ITRF)
Survey instruments	In the air Airborne magnetometer: Scintrex CS-2 Cesium magnetometer Data acquisition system: Industrial PC with a LCD monitor GPS receiver: csi wireless DPGS MAX Laser altimeter: RIEGL LD-90-3300HR Infrared video camera: Inframetrics PM-150 On the ground Ground magnetometer: Scintrex CS-2 Cesium magnetometer
Helicopter operation	ICARUS (Italy)

Fig. 5 Picture of the survey helicopter (AS350 B2) employed for the high-resolution aeromagnetic survey over the Vulcano-Lipari volcanic complex in 2002.

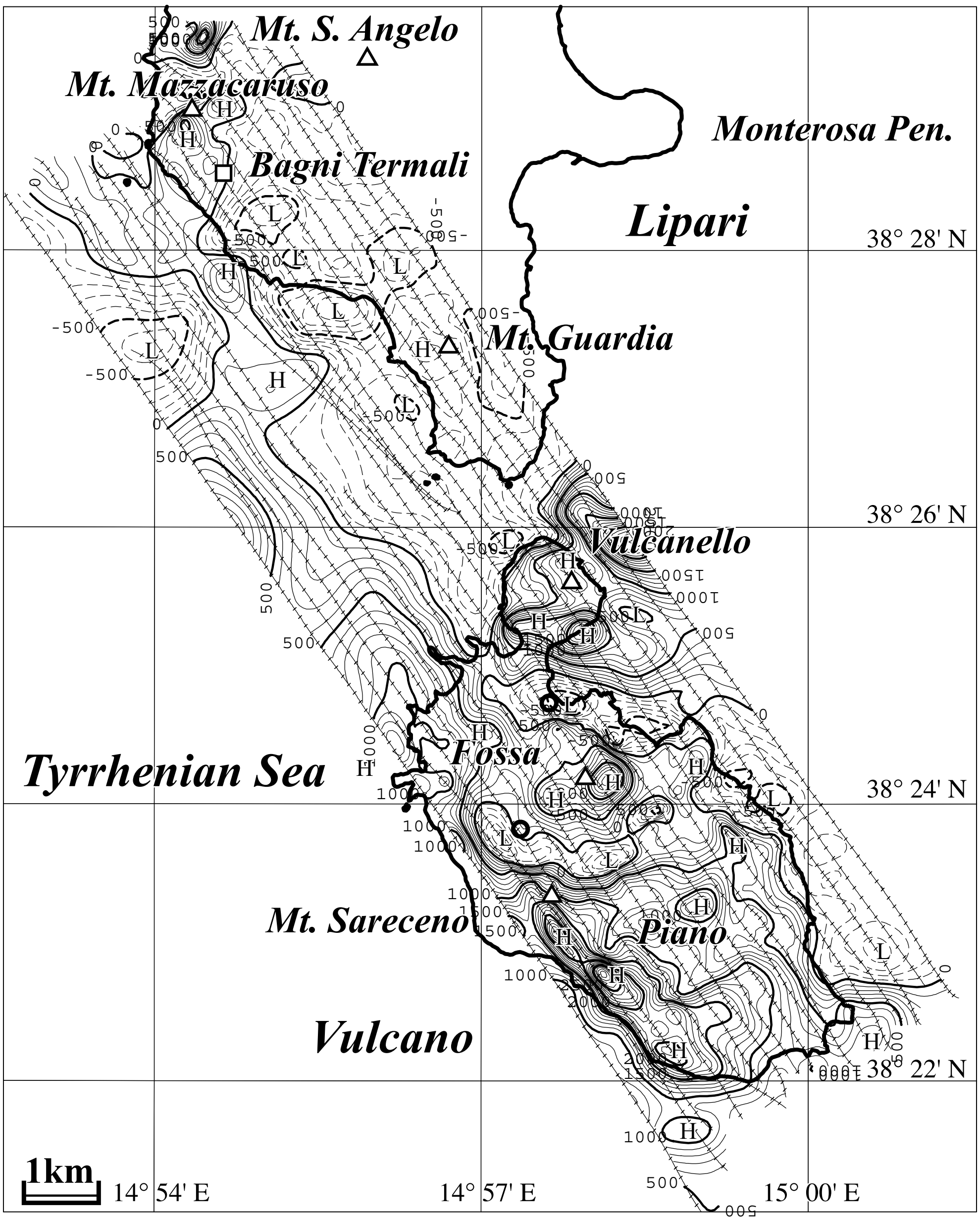

Fig. 6 Total magnetic intensity anomaly map of Vulcano and Southern Lipari in 2002. The data were reduced onto the surface parallel to and 150 m above a smoothed terrain and sea surface. H and L show magnetic highs and lows, respectively. Knotted lines indicate track line paths. Contour interval is 100 nT. See also Fig. 3.

and some corrections for diurnal magnetic variation and heading error were applied, and the reference field model IGRF was removed from the observed data. Magnetic anomalies of the 2002 survey on the surface parallel to and 150 m above a smoothed terrain and sea surface (Fig. 6) were calculated from the observed data by an iterative method, assuming equivalent anomalies on a surface lower than the observed surface (Nakatsuka and Okuma, 2006). Real-time DGPS data have been used for 3-D positioning for the 2002 survey. The flight altitude of 1999 survey has been reconstructed by the laser altitude and detailed DEM data (Gwinner *et al.*, 2000) and magnetic anomalies on the same surface as the 2002 survey were calculated (Fig. 7).

Comparisons between the 1999 and 2002 survey data have been conducted on the common surface parallel to and 350 m above a smoothed terrain and sea surface to monitor the volcanic activity of the area. The subtraction (Fig. 8) of the 1999 data from the 2002 data indicates high-frequency residuals especially in magnetically high-gradient areas on Vulcano. The differ-

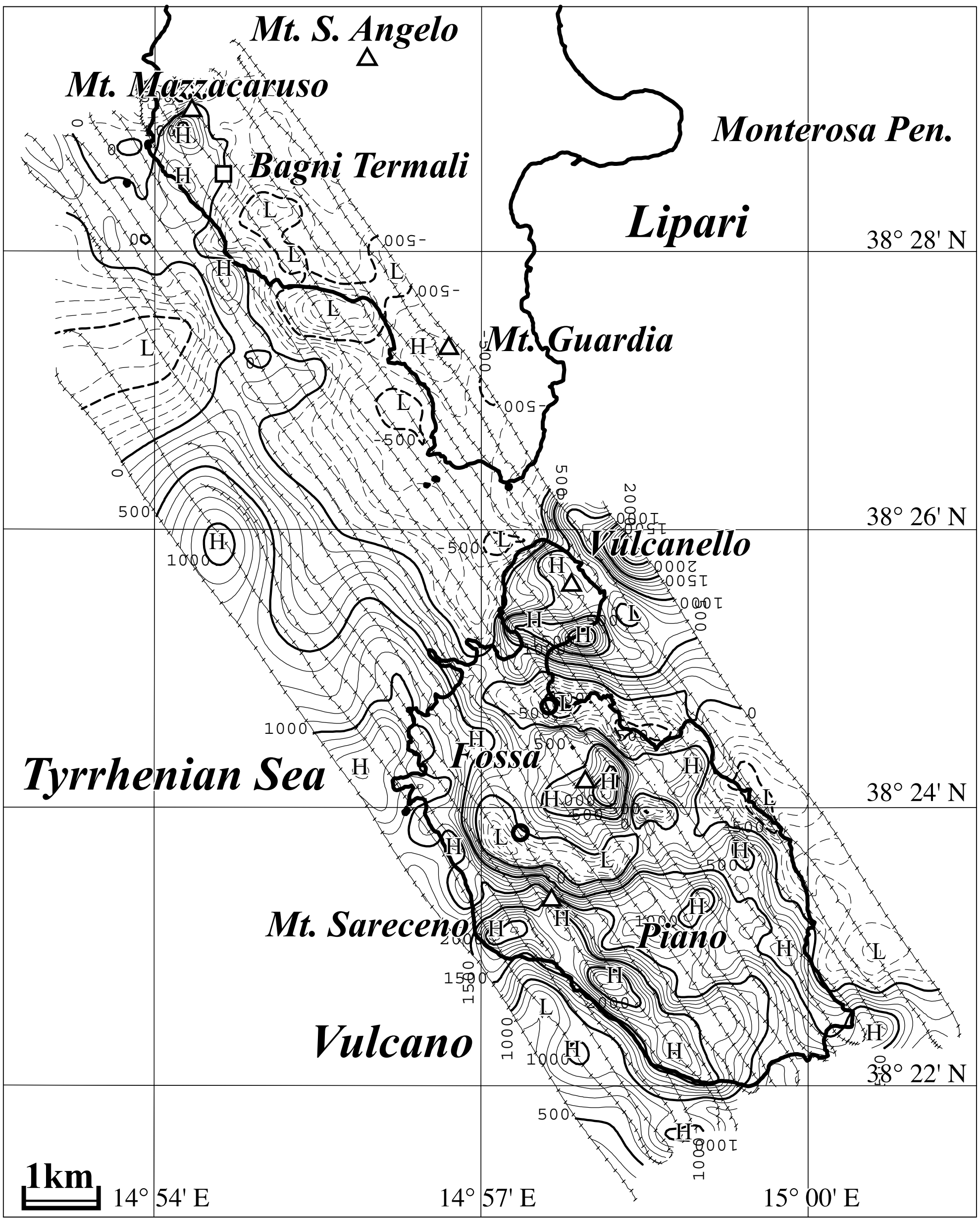

Fig. 7 Total magnetic intensity anomaly map of Vulcano and Southern Lipari in 1999. See also Fig. 6.

ences were caused probably by aliasing because of an insufficient survey line spacing for such areas and altitude error based on different positioning methods: a GPS/GLONASS system and laser altimeter for the 1999 survey and a real-time DGPS (3-D positioning) for the 2002 survey. These conditions imply that it is difficult to judge if there were meaningful changes related to volcanic activity between the two surveys. Therefore, we proceeded to compile a magnetic anomaly map based mainly on the 2002 survey data with an additional inclusion of four profiles from the 1999 survey to cover a larger area than the individual surveys. Total magnetic intensity anomalies on the surface parallel to and 150 m above a smoothed terrain and sea surface were complied (Fig. 9; appendix map).

5. Magnetization intensity mapping and characteristics of magnetic anomalies

Magnetic terrain correction (Grauch, 1987) was applied to the merged magnetic anomalies (Fig. 9) to reduce magnetic effects by terrain, assuming a magnetic structure comprised of an ensemble of prism models extending from the ground surface to a depth of 2,000 m below sea level. The bottom depth was assumed from the fact that a high temperature of more than 419 degrees C was measured at the bottom (1975

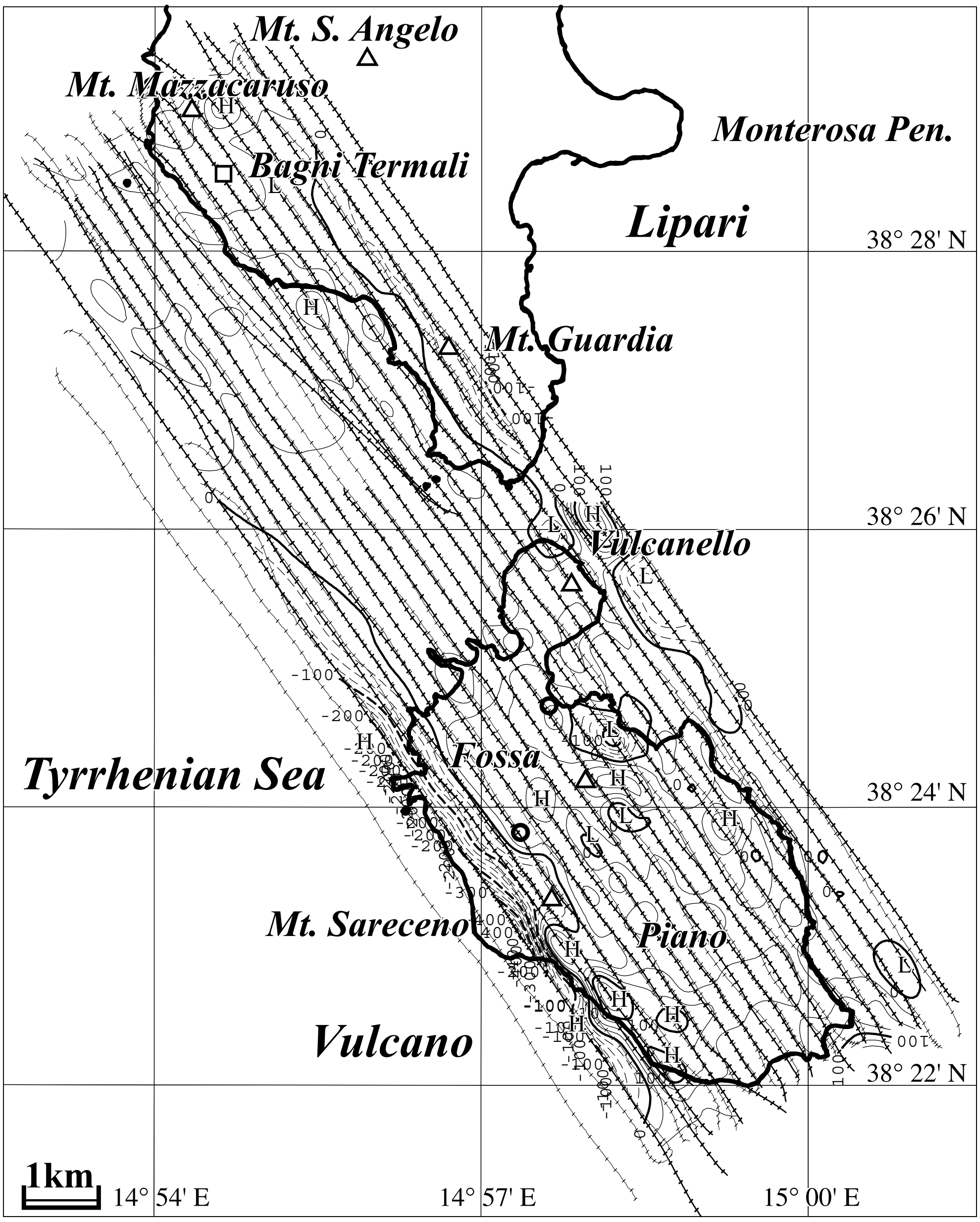

Fig. 8 Magnetic anomaly difference between the 1999 and 2002 survey data on the common surface parallel to and 350 m above a smoothed terrain and sea surface Thin and thick knotted lines indicate the 1999 and 2002 track line paths, respectively. Contour interval is 25 nT. See also Fig. 6.

m BSL) of a geothermal drill hole into the southern foot of Fossa Cone (e.g. Faraone *et al.*, 1986). The optimum magnetization intensity depends on the area of calculation. It was calculated 2.0 A/m for the whole study area. This value was adopted for the terrain correction and terrain-corrected anomalies were calculated by a subtraction of synthetic anomalies from the merged anomalies (Fig. 9).

Apparent magnetization intensity mapping (Nakatsuka, 1995) was applied to the terrain-corrected magnetic anomalies. Apparent magnetization intensities were calculated (Fig. 10) assuming the same model as the magnetic terrain correction. Reduction to the pole anomalies on the surface parallel to and 150 m above a smoothed terrain and sea surface (Fig. 11; appendix map) were also calculated simultaneously with the calculation of magnetization intensity and the rotation of the directions of magnetization and ambient magnetic field with an inclination of 54°N and a declination of 2°E to vertical (Nakatsuka and Okuma, 2006).

According to the reduction to the pole anomaly map (Fig. 11; appendix map), there is an obvious regional magnetic difference between the southern Lipari and Vulcano. Magnetic highs are distributed mainly over

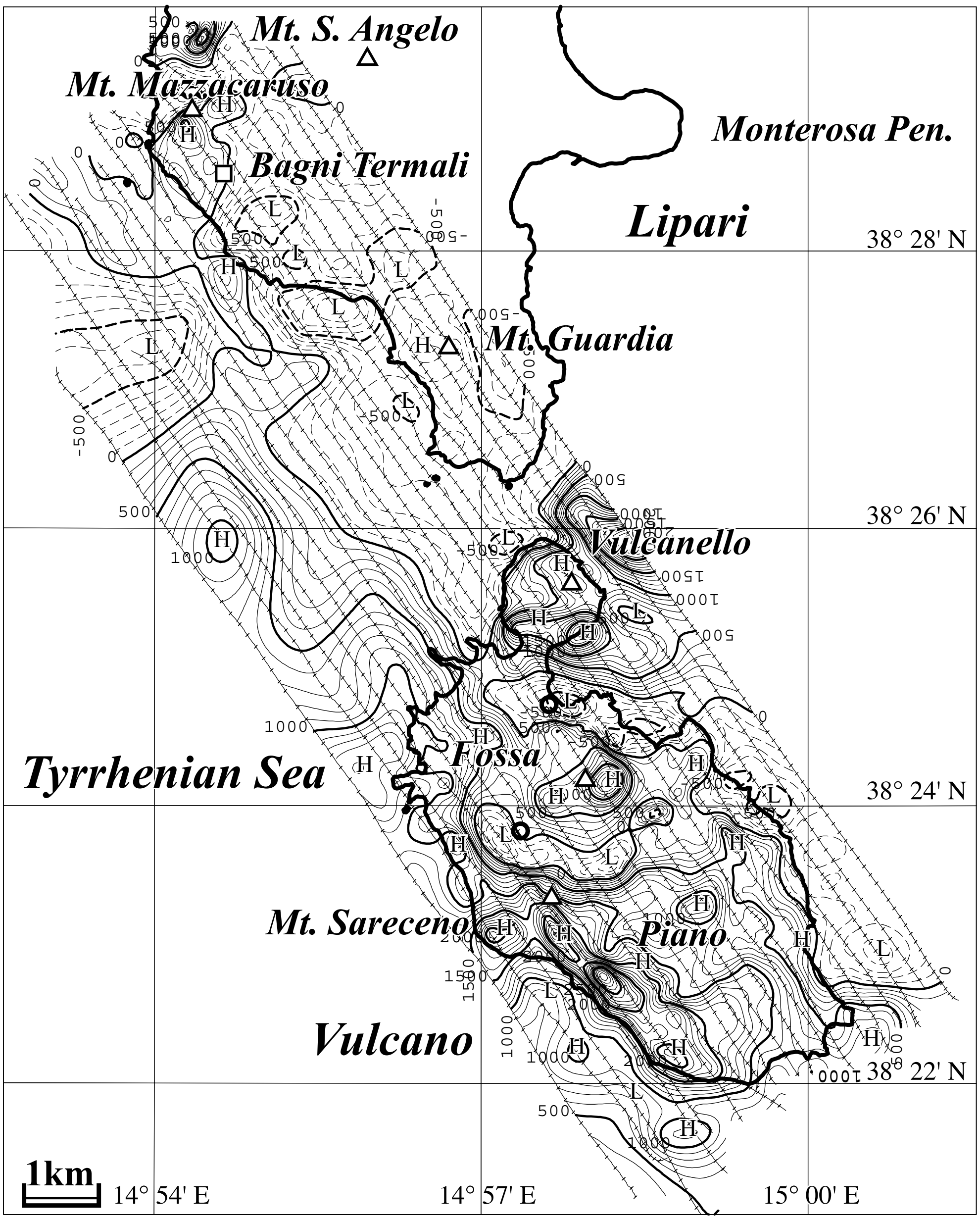

Fig. 9 Total magnetic intensity anomaly map of Vulcano and Southern Lipari compiled from the 1999 and 2002 survey data. The data were reduced onto the surface parallel to and 150 m above a smoothed terrain and sea surface. See also Fig. 6.

Vulcano, even though intense volcanic activities have occurred on both islands. This can be interpreted by a petrologic difference between volcanic rocks composing the two islands. Lipari Island is composed mainly of silicic volcanic rocks such as rhyolites with an exception of andesitic rocks on the west coast, whereas Vulcano Island is composed chiefly of volcanic rocks from trachyte to tephrite with some minor rhyolite flows.

The reduction to the pole anomaly map (Fig. 11) also shows detailed geologic signatures. By comparison with the geologic map (Fig. 4), it can be seen that magnetic highs lie on trachybasaltic-trachyandesitic lava flows on the flank of Primordial Vulcano (South Vulcano). Magnetic highs are also distributed inside Piano Caldera, suggesting underlying thick parts of lava flows. Along the rim of Piano Caldera, magnetic highs also exist, corresponding to exposures of leucite-tephritic lava flows filling Piano Caldera (Keller, 1980).

Inside Fossa Caldera, scattered magnetic highs can be identified in the region of Fossa Cone. Some of them apparently correspond to lava flows from the Fossa volcano: trachytic lava flows at Punta Nere (5,400 ± 1,300 YBP) (Frazzetta and La Volpe, 1991; Fig. 4) and

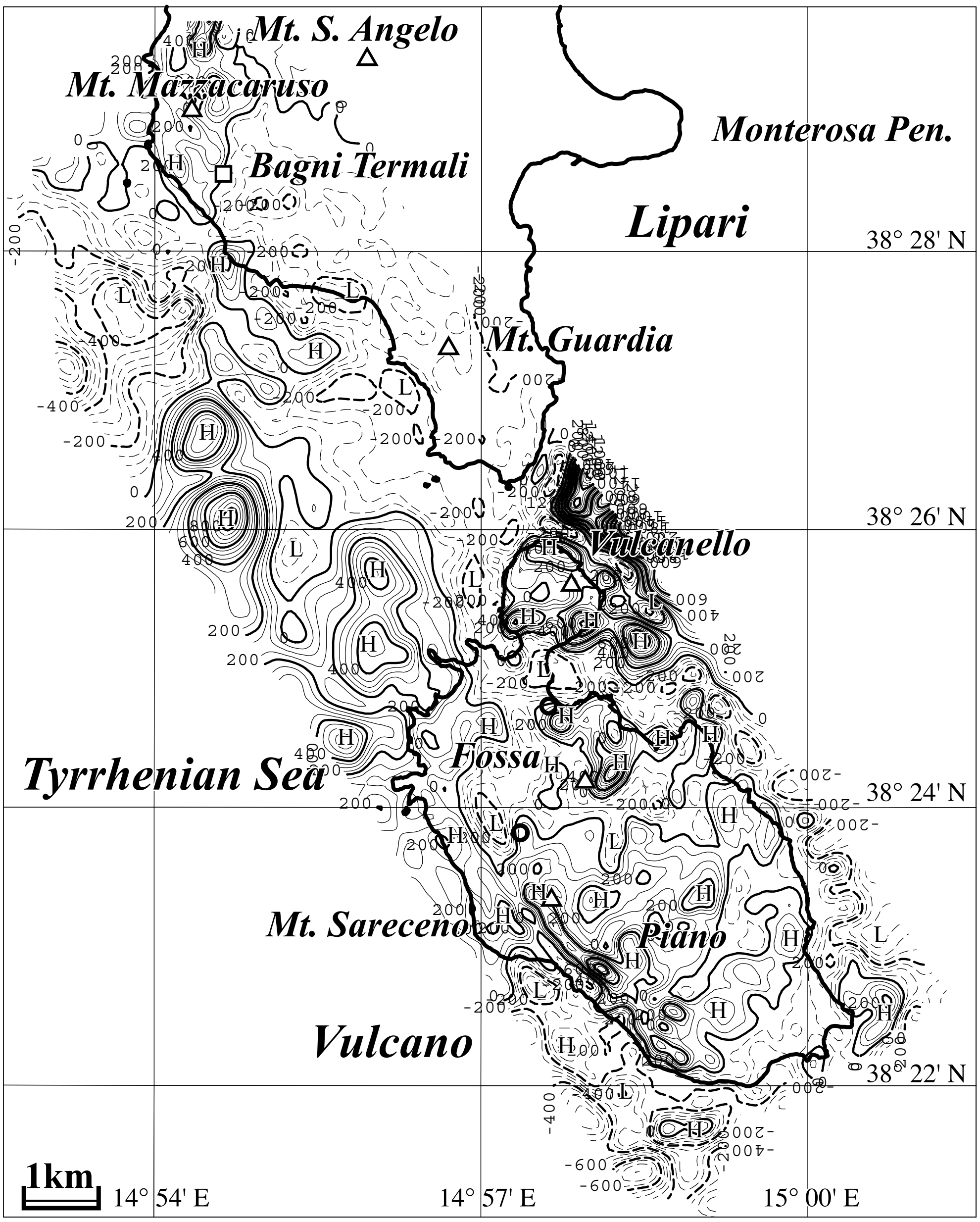

Fig. 10 Apparent magnetization intensity map of Vulcano and Southern Lipari calculated from terrain-corrected magnetic anomalies with an assumed magnetization intensity of 2.0 A/m. Values are in 0.01 A/m with the contour interval of 50 in this sheet. See also Fig. 6.

Campo Sportivo (4,600±1,950 YBP). No specific signatures can be found on the rhyolitic flow (Commenda flow; 785 AD) and trachytic flow (Palizzi flow; 1,600±1,000 YBP) in the southern flank or obsidian flow (Pietre Cotte; 1739 AD) in the northern flank.

An apparent magnetic high is distributed east of the present crater rim of Fossa Cone, suggesting the subsurface existence of lava flows covered by younger pyroclastic deposits. A magnetic high also lies on the northern flank between phreatic craters, Forgia Vecchia I and II (1727 AD) and Levante Port on Vulcano, suggesting the subsurface existence of magnetic rocks such as lava flows. This area is underlain by thick (~400 m) latitic lava flows confirmed by deep drilling (Vulcano Porto 1; Gioncada and Sbrana, 1991). The results of modeling these magnetic highs are explained in Okuma *et al.* (2006).

The tephritic-trachytic lava platform in the Vulcanello Peninsula is bounded by several magnetic highs while a magnetic low occupies pyroclastic cones and their surrounding areas, indicating a magnetic difference in the geology.

On the west coast of Lipari, magnetic highs are dis-

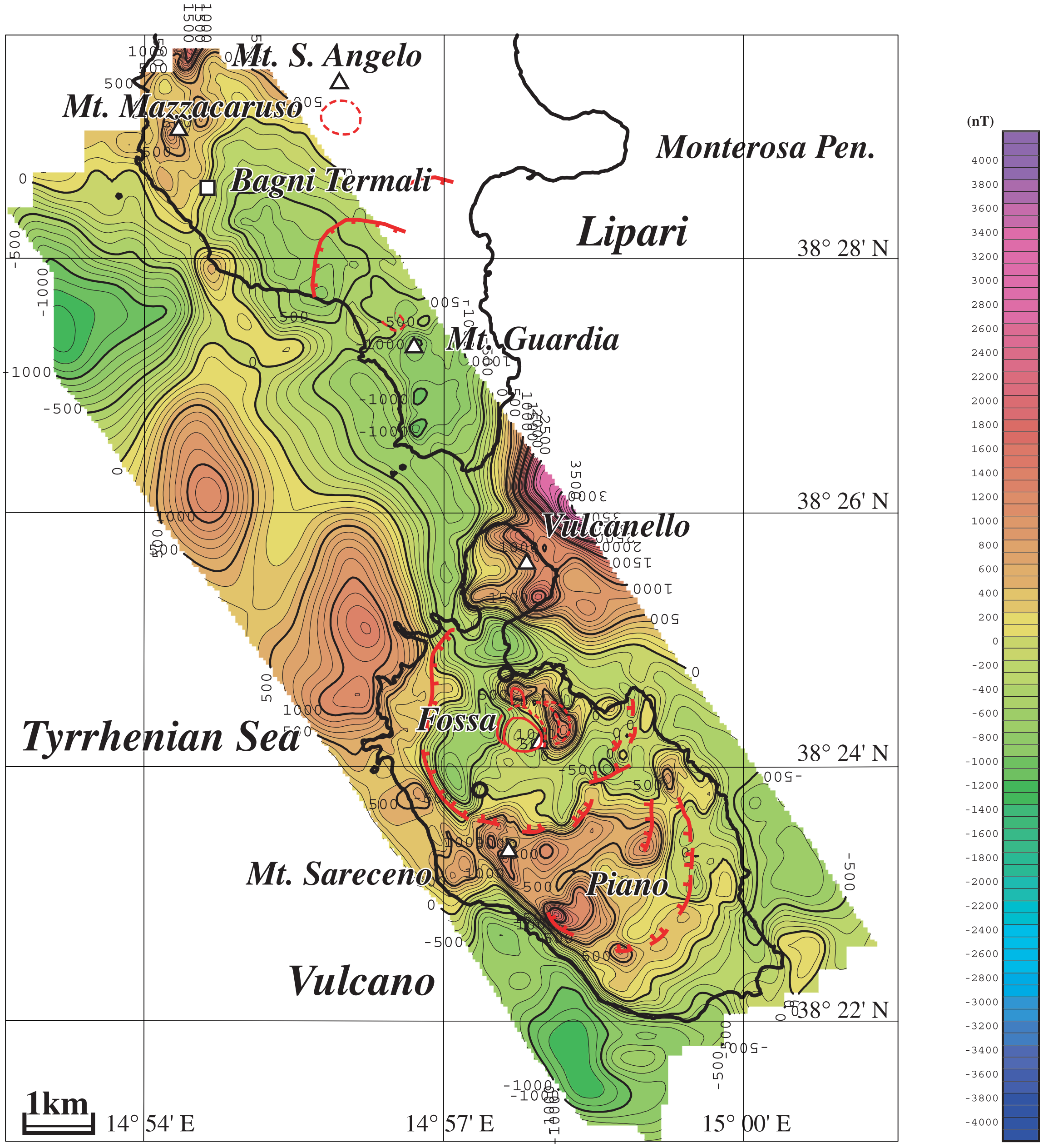

Fig. 11 Reduction to the pole anomaly map of Vulcano and Southern Lipari calculated from the apparent magnetization intensities of the terrain model (Fig. 10). Contour interval is 100 nT. Red solid lines, and toothed solid lines indicate craters and calderas as in Fig. 4. See also Fig. 9.

tributed in the Mt. Mazzacaruso area, corresponding to the exposure of andesitic lavas (cycle I; Pichler, 1980). The offshore area between Lipari and Vulcano islands is occupied mostly by magnetic highs but the relationship between magnetic anomalies and submarine topography (Fig. 3) is not clear. Offshore of the southeastern edge of Vulcano, lies a magnetic high, and this corresponds to a submarine terrace (Gabbianelli *et al.*, 1991), implying its volcanic origin.

6. Conclusions

In collaboration with the GBA, the Geological Survey of Japan, AIST conducted a helicopter-borne aeromagnetic survey over the Vulcano-Lipari volcanic complex, the Aeolian Islands, Italy in 2002 and compiled a high-resolution aeromagnetic anomaly map of the area by merging the 1999 and 2002 survey datasets. Apparent magnetization intensity mapping was then applied to terrain-corrected magnetic anomalies, and a reduction to the pole anomaly map was also calculated at the same time. These magnetic maps showed detailed characteristics of the magnetic anomalies, suggesting heterogeneity of the subsurface structure of the area, as well as general characteristics.

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イタリア・ブルカノーリパリ火山地域高分解能空中磁気異常図

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要　旨

産業技術総合研究所では，1999年以来，オーストリア地質調査所（GBA）と，イタリア・エオリア諸島の火山災害軽減のため，物理探査による詳細な地下構造調査と同調査の繰り返し実施による火山活動のモニタリングに係わる研究を実施している（大熊ほか，2001）．2000年からは当該地域で重力探査を開始し，広域の調査を行うとともに，ブルカノ火山のフォッサ火砕丘では測線上で高密度重力探査を実施し，重力異常の特徴を明らかにしている（駒澤ほか，2002；Sugihara *et al.*, 2002）．

2001年には，GBAと産業技術総合研究所地球科学情報研究部門（現地質情報研究部門）との間で研究協力協定を結び，翌2002年には，ブルカノ火山 - リパリ火山南部で高分解能空中磁気探査を実施している．今回2002年の調査の結果得られた空中磁気データに加え，1999年にGBAが測定したデータを取り込んで，当該地域の高分解能空中磁気異常図を編集した．

2002年に行った高分解能空中磁気探査の観測データから，等価異常を仮定した処理法（Nakatsuka and Okuma, 2006）により，平滑化した地形及び海水面から高度150 mの滑らかな曲面上での磁気異常分布を求めた．当該地域では，1999年にほぼ同一の測線上でGBAが高分解能空中磁気探査を実施しており，3年間の地磁気変化を検出するため，同一の高度面上での磁気値を比較検討した．その結果，地磁気変化は認められるものの，その原因として，観測点高度の決定法が二調査間で異なることと，地形及び地磁気変化が大きな地域で比較的顕著な相違が認められエリアシングの影響が疑われることから，現状では変化の有無の本質的な議論には至らないと判断された．そこで，2002年の測線データを基本として，周辺部に位置する1999年の一部の測線データを利用して，可能な限り広域をカバーする磁気異常図を編集した．その結果，リパリ火山南部からブルカノ火山全域を含む地域の詳細な磁気異常分布が明らかとなった．これによると，流紋岩質火山岩を主体とするリパリ火山南部は顕著な磁気異常は少なく，代わってブルカノ火山では，各所に顕著な高磁気異常が分布する．

ついで，磁気異常分布と地表地質分布との関係を詳細に検討するため，磁化強度マッピング（Nakatsuka, 1995）を行い，磁化強度分布図と極磁力異常図を作成した．この際，相関法により求めた当該地域全域の平均磁化（2.0 A/m）による地形補正量を計算し，観測磁気異常から除いた値を解析対象とした．得られた極磁力異常図によれば，特にブルカノ火山の磁気異常の詳細が明らかとなった．地質図との比較により，南部の古期楯状火山（南ブルカノ）の山腹やピアノカルデラに分布する粗面玄武岩や粗面安山岩溶岩に対応して，高磁気異常が認められる．また，北部のフォッサカルデラでは，フォッサ火砕丘から噴出したトラカイト - テフライト溶岩に対応して高磁気異常が認められる一方，流紋岩質黒曜岩溶岩の分布に対応しては磁気異常は認められない．フォッサ火砕丘の北側斜面（Forgia Vecchia）及び東側斜面においては，地表兆候はないものの局所的な高磁気異常が分布し，その他の地球科学的情報を考慮した磁気異常の解析・解釈から，フォサ火口に加え，多量の溶岩を噴出しフォッサカルデラを埋積したかつての噴火中心が複数伏在する可能性が示唆されている（Okuma *et al.*, 2006）．