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The monzogabbroic intrusion in the island of Vulcano, Aeolian Archipelago, Italy

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Abstract. Two drill-holes were carried out during 1983–84 by the "Joint Venture" AGIP-EMS-ENEL on the island of Vulcano southwest of the Cratere della Fossa. After passing through pyroclastics and lavas of the young volcanic centres of Vulcano the drill-holes penetrated an intrusion of monzogabbro to leuco-monzogabbro composition. In one of the holes the top of the intrusion occurs at 1360 m and the intrusive rocks are found to the bottom of the well at 2050 m. At this depth the temperature exceeds 419 °C and the temperature gradients are sufficiently steep that magma could well be reached only a few hundred metres deeper. Lava of the South Vulcano centre is metamorphosed by the intrusion.

A massive pyroclastic bed, underlying the welded scoriae deposits associated with collapse of the Caldera del Piano system, contains blocks of the intrusion. Radiometric data suggest an intrusion age of 30 000 years. Geophysical data indicate that the main intrusion is a shallow level and is located in the stretch of sea west of Mt. Lentìa.

Introduction

The island of Vulcano is the southernmost of the seven islands forming the Aeolian Archipelago in the Tyrrhenian Sea north of Sicily. Together with Stromboli, it represents an active volcanic structure, the activity starting during the Upper Pleistocene with the formation of the South Vulcano centre.

Vulcano consists entirely of lava flows and pyroclastics. Keller (1980) identified four main volcanic centres (Fig. 1): the South Vulcano and Caldera del Piano centre; the Lentìa centre; the Caldera della Fossa and Fossa di Vulcano centre; the Vulcanello centre.

The South Vulcano centre is a composite structure consisting of a large stratocone with truncated summit due to multiple collapse. The circular collapse depression (2–2.5 km across) is called the Caldera del Piano. Subsequent activity inside and around the caldera rim filled the caldera with pyroclastic deposits and lava flows, of almost identical composition to the lavas and the dykes of the old stratocone. According to the classification of De La Roche et al. (1980) these rocks are olivine basalts and latibasalts (see Fig. 5).

The Lentìa centre forms the rocky hills at the western edge of the Caldera della Fossa. Emplaced in the Upper Wurm, the centre mainly consists of a pile of thick, highly viscous rhyodacitic lava flows with subordinate extrusive domes. Basaltic lavas outcrop at the base, whereas largely subordinate dacites occur at the top.

The Caldera della Fossa centre began to develop at the end of last glaciation. Several pyroclastic deposits and two hawaiitic lava flows on the western flank of Mt. Saraceno are attributed to its activity (Keller 1980). The Fossa di Vulcano is the active crater of the island. Its steep stratocone, occupying a large area of the Caldera della Fossa, rises from sea level up to 391 m, with a multiple crater structure due to a progressive migration of the eruptive vent in a WSW direction. The last eruption of the Fossa took place in 1888–1890 (Mercalli and Silvestri 1891). Currently, fumarolic activity occurs on the northern rim of the crater. The beginning of the Fossa formation is younger than 8500 B.C. (Keller 1980; Gillot and Villari 1980). The predominant products of the Fossa activity are pyroclastics. The lava flows of Piano Porto, Palizzi and Punte Nere are mugearitic in composition and at Commenda and Pietre Cotte are rhyolitic obsidians.

Vulcanello appeared as a new island north of the Fossa in 183 B.C. and was connected with Vulcano by sand accumulation in the isthmus area probably in the second half of the sixteenth century (De Fiore 1922). The centre is constructed by a lava platform and three closely spaced volcanic cones located on an ENE-WSW structural trend. The platform lavas and the lava flows of Vulcanello I (eastern cone) are hawaiites, whereas the lava flow emitted from the northern flank of Vulcanello II (middle cone) is a mugearite.

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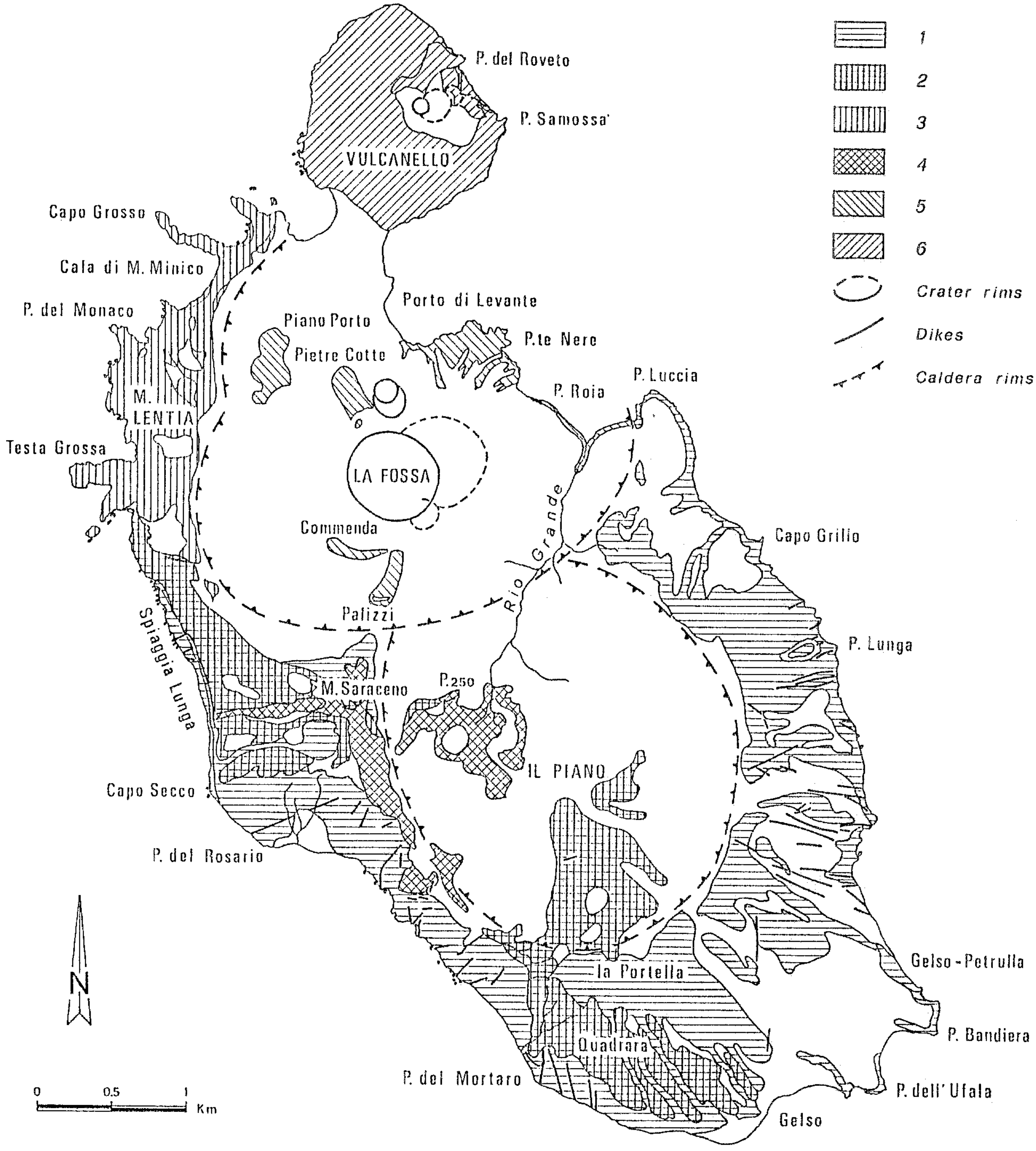

Fig. 1. Simplified geological sketch map of Vulcano island, after Keller (1970). Analyses of the volcanics are plotted in Figs. 2 and 5. *1, 2* South Vulcano and Caldera del Piano; *3* Lentìa; *4,5* Caldera della Fossa and Fossa di Vulcano; *6* Vulcanello

Vulcano's rocks are potassic in character (Fig. 2). Both the petrochemistry and the mineralogy of the island's rocks belong to the shoshonitic magma series.

Multiple-stage drilling was carried out in 1983–1984 by the "Joint Venture" AGIP-EMS-ENEL, during exploration for a geothermal reservoir. The borehole IS.V.1 southwest of Gran Cratere or Fossa (point 38°23′46″ N, 2°30′17″ E), reached a depth of 2050 m. The drill-hole first penetrated chaotic pyroclastic deposits of the Fossa centre to a depth of 160 m. Between 160 and 420 m (Fig. 3) lavas and pyroclastic deposits belonging to the Caldera della Fossa centre were found. A welded scoria of the Caldera del Piano centre was recovered between 420 and 500 m depth. From approximately 500 m to 1360 m depth la-

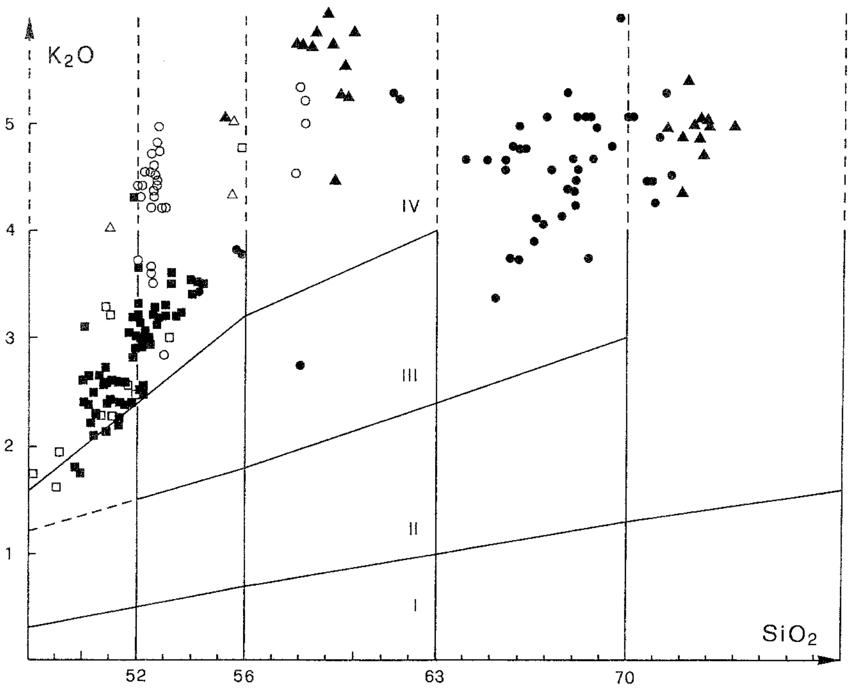

Fig. 2. K_2O vs SiO_2 plot for the volcanics from Vulcano island. *I* low-K calc-alkaline series; *II* calc-alkaline series; *III* high-K calc-alkaline series; *IV* shoshonite series; after Peccerillo and Taylor (1976). *Full squares* =South Vulcano; *open squares*=Caldera del Piano; *full circles*=Lentìa; *open triangles* =Caldera della Fossa; *full triangles*=Fossa di Vulcano; *open circles*=Vulcanello. Data sources: Baldanza et al. 1973; Bini et al. 1974; Brunacci et al. 1976; Faraone, unpublished data

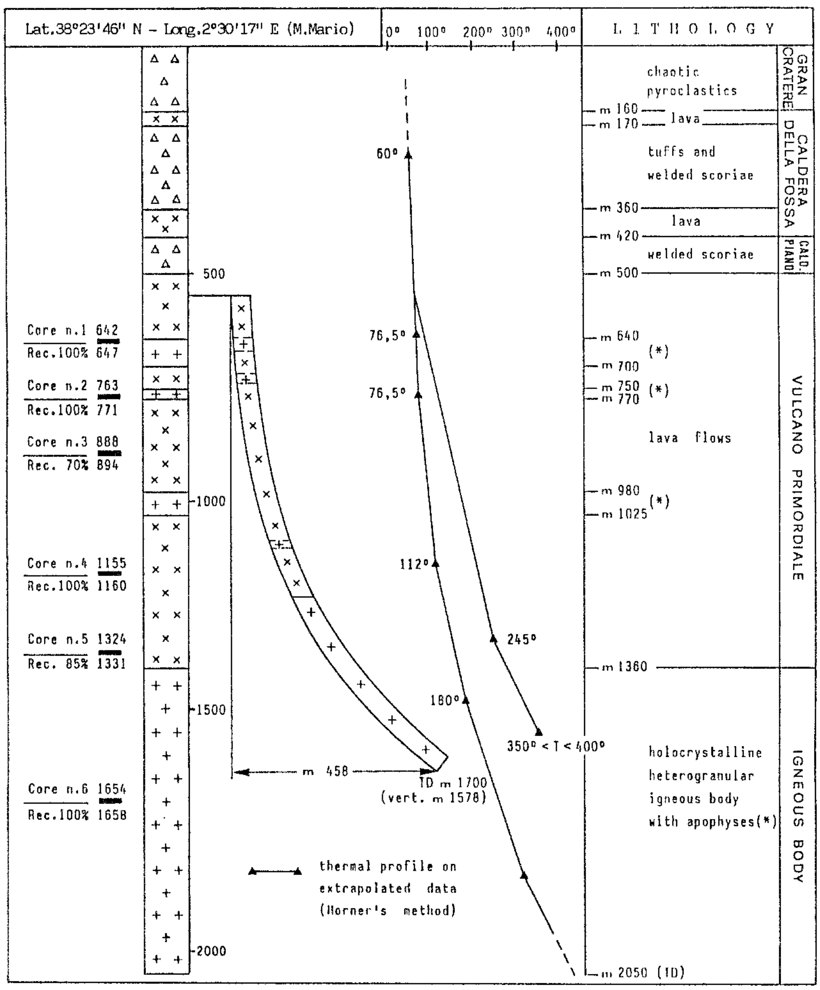

Fig. 3. Well IS.V.1/1DIR, Vulcano island: summary. Redrawn from Silvano (1985)

vas, often in a brecciated condition, were identified as belonging to the South Vulcano (Vulcano Primordiale) centre. In these lavas the drill-hole encountered vein injections of a holocrystalline heterogranular rock at approximately 640–700 m, 750–770 m and 980–1025 m. From 1360 m downwards an intrusion was penetrated.

The well encountered rapidly increasing temperatures from approximately 1140 m to the bottom at 2050 m, where the temperature exceeded 419 °C (the melting point of zinc). Associated with this temperature increase a particularly low permeability was noticed (no circulation losses on drilling).

A second well (1DIR) was drilled which deviated to the north and reached a vertical depth of 1578 m, with a lateral shifting of 458 m (Fig. 3). It penetrated the same vein injections, reaching the intrusion at approximately 1160 m. This hole found higher temperatures at shallower depths: 243 °C at 1338 m and between 350 °C and 400 °C at the bottom.

During the drilling of the two boreholes, coring was carried out at different depths (Fig. 3). Samples of the intrusive body taken at 1654–1658 m (IS.V.1, core 6) from the vertical well and at 1476.4–1490 m from the northwards deviated well (1DIR) were examined. Samples collected at 764.5–770.4 m (IS.V.1, core 2) from the vertical well, within a vein, were also examined.

The monzogabbroic intrusion

The intrusive rock sampled between 1654–1658 m is dark grey and heterogranular, with plagioclase and augite crystals reaching 5–6 mm in length. Other primary components are K-feldspar, magnetite and apatite. The plagioclase and augite tend to be idiomorphic whereas K-feldspar is always interstitial. Small plagioclase crystals also contribute to the formation of the groundmass.

The plagioclase, frequently with small patches and oscillatory zoning marked by very fine inclusions, has albite-Carlsbad, albite-pericline and rarely albite-Ala B twinning, and has $2V_Z$ 82 ± 2 °, giving a composition of An_{58-65} LT determined by the twinning. Compositions of An_{60-65} were also obtained by means of powder X-ray analyses plotted on a $\Delta(\vartheta)_1$-% An diagram (Bambauer et al. 1967). The K-feldspar is microperthitic, shows Carlsbad twinning and is partly sericitized.

Table 1. Monzogabbro (samples *a*, *b*, *c* and *B*, *C*, *D*) and recrystallized lava (sample 4) from Vulcano island. Major element analyses and CIPW norm

	a	*b*	*c*	*B*	*C*	*D*	4
SiO_2	49.26	48.64	48.65	49.54	53.16	53.39	52.23
TiO_2	0.80	0.71	0.84	0.66	0.60	0.59	0.85
Al_2O_3	18.45	18.58	17.84	19.73	20.78	19.39	17.49
Fe_2O_3	5.30	5.16	6.09	7.45	4.53	4.08	3.30
FeO	3.63	3.85	3.88	4.00	2.68	2.83	3.66
MnO	0.10	0.09	0.14	0.12	0.10	0.06	0.07
MgO	4.14	4.21	4.39	2.72	1.54	1.93	6.37
CaO	10.34	10.69	11.48	6.13	6.32	7.73	10.03
Na_2O	3.68	3.13	3.13	4.03	4.13	4.05	4.32
K_2O	2.47	2.90	2.23	3.97	4.77	4.68	1.15
P_2O_5	0.35	0.21	0.29	0.33	0.38	0.45	0.18
H_2O^+	0.67	0.64	0.59	0.86	0.62	0.39	0.71
H_2O^-	0.06	0.12	0.07	0.26	0.06	0.05	0.13
CO_2	0.36	0.59	—	—	—	—	0.49
S	tr	tr	—	tr	—	—	tr
total	99.61	99.52	99.62	99.80	99.67	99.62	100.98
R_1	1142	1195	1325	626	756	8.27	1469
R_2	1674	1717	1796	1178	1160	1303	1732
CIPW							
or	14.60	17.14	13.18	23.46	28.19	27.66	6.80
ab	24.69	20.43	21.14	27.67	29.91	26.70	36.34
an	26.53	28.08	28.04	24.02	24.08	20.91	24.94
ne	3.49	3.28	2.90	3.48	2.73	4.10	0.11
di	15.91	15.72	21.23	3.31	3.77	11.51	16.27
ol	2.82	3.46	1.38	3.91	1.73	0.23	7.75
mt	7.68	7.48	8.83	10.80	6.57	5.92	4.78
il	1.52	1.35	1.60	1.25	1.14	1.12	1.61
ap	0.83	.50	0.69	0.78	0.90	1.07	0.43
cc	0.82	1.34	—	—	—	—	1.11

Analyst E. Pagana. Depths of samples: IS.V.1, $a=1654$ m, $b=1655.5$ m, $c=1658$ m, $4=767.1$ m; 1DIR, $B=1477.9$ m, $C=1479.3$ m, $D=1482.4$ m

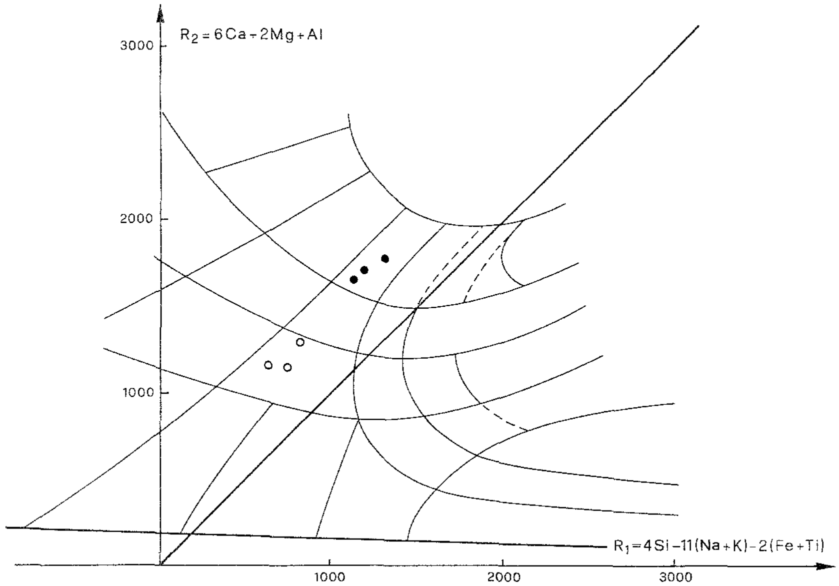

Fig. 4. Composition of plutonic rocks of Vulcano island plotted on an R_1R_2 diagram (De La Roche et al. 1980). *Full circles* = monzogabbroic (alkali gabbro) rock; *open circles* = the same altered by hydrothermal processes

The augite, with Z∧c 45–48 ° and $2V_Z$ 56±2 °, is often multiply twinned on {100}. The pyroxene is in some cases completely altered by hydrothermal processes into an aggregate of very abundant biotite, chlorite, calcite and fine-grained magnetite with sporadic pyrite and hematite. The alteration begins with the appearance of small patches of biotite inside and around the crystals. Biotite aggregates are also found around primary magnetite.

Excluding the aggregates deriving from the hydrothermal alteration of the augite, the average modal composition is: plagioclase 60.0; augite 17.4; K-feldspar 7.3; magnetite 4.3; apatite 0.2; biotite 4.0. The rock is defined as monzogabbro.

A K/Ar whole rock age determination carried out at CNRS, Vandoeuvre-les-Nancy (France), supplied the following results with an average value around 30 000 years: K% = 1.61; $^{40}Ar = 0.002023 \times 10^{-6}$ cc/g; $T = 0.032$ Ma ± 0.023 Ma (constants used: $\lambda_\beta = 4.962 \times 10^{-10}$ an^{-1}; $\lambda_\gamma 0.581 \times 10^{-10}$ an^{-1}; $^{40}K = 0.01167$ atom%). For obvious considerations these data merely indicate a very young age.

Samples of the intrusion taken between 1476 and 1490 m depth from the second well show the same textural characteristics, but with a much greater abundance of K-feldspar and less augite. The rock is defined as a leuco-monzogabbro, but is profoundly hydrothermally altered. The following secondary minerals are found: hornblende, biotite, tremolite, pistacite, penninite and andradite.

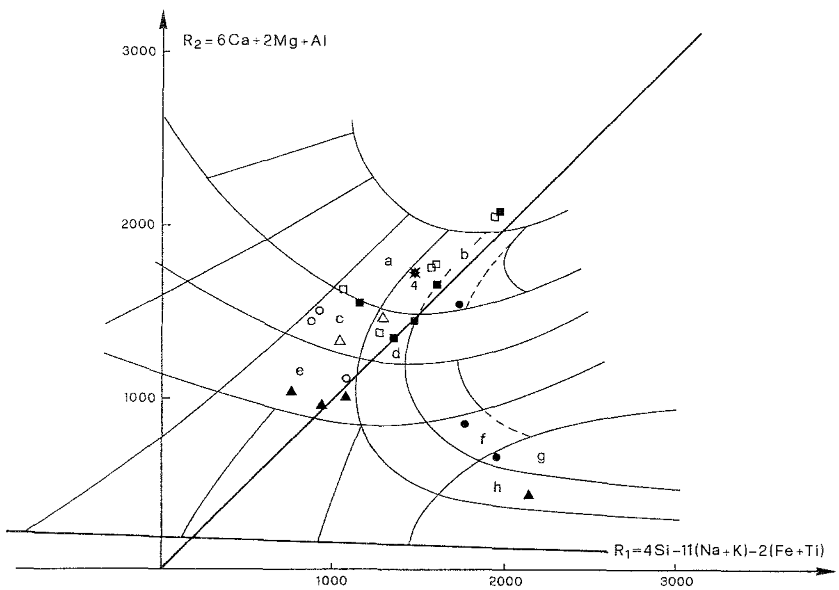

Fig. 5. Composition of sample 4 and average compositions of volcanics of Vulcano island plotted on the R_1R_2 diagram of De La Roche et al. (1980). *a*, alkali basalts; *b*, olivine basalts (u.s., s., o.s.); *c*, hawaiites; *d*, lati-basalts; *e*, mugearites; *f*, dacites; *g*, rhyodacites; *h*, rhyolites. Symbols as in Fig. 2

Table 1 gives the chemical analyses and the CIPW norms of three samples *a*, *b* and *c* from the vertical borehole and of three samples *B*, *C* and *D* from the northwards deviated borehole.

Plotted on the R_1R_2 diagram of De La Roche et al. (1980), samples *a*, *b* and *c* fall within the range of alkaline gabbros (Fig. 4). On the other hand we do not believe that the chemical data relevant to samples *B*, *C* and *D* of the northwards deviated borehole can be used for classification, owing to the abundance of secondary minerals in the samples.

The core from 763–771 m

The core taken between 763 m and 771 m (IS.V.1, core 2) is a breccia. The fragments are enclosed by a dark grey-green matrix which has been highly altered hydrothermally to chlorite, clay minerals (montmorillonite?), calcite, anhydrite, pyrite, limonte and abundant quartz.

From 763 m to approximately 766.5 m the fragments are composed of holocrystalline heterogranular rock referable to a vein intrusion. From approximately 766.5 m to about 767.5 m, these fragments are mixed with lava fragments, many of which are recrystallized; and then, from about 767.5 m downwards, the fragments are composed exclusively of lava.

The borehole evidently penetrated an intensely brecciated contact zone between the vein and lava. The brecciation was probably caused by the Caldera del Piano's multiple collapse; the resulting vertical discontinuities would have acted as ascending pathways for hydrothermal fluids.

The fragments in the vein rock are heterogranular with idiomorphic plagioclase and clinopyroxene and interstitial K-feldspar, magnetite and needle-shaped apatite. The groundmass is obliterated by chlorite which, together with calcite, penetrates along fractures through the phenocrysts. The longer plagioclase crystals, with dimensions up to 7–8 × 2–2.5 mm, are strongly oriented. The pyroxene is found in rough prisms and reaches a maximum dimension of 5–6 mm. The plagioclase composition obtained from the twinning is An_{62} LT, confirmed by plotting on a $\Delta(\vartheta)_1$-% An diagram. The pyroxene, how-

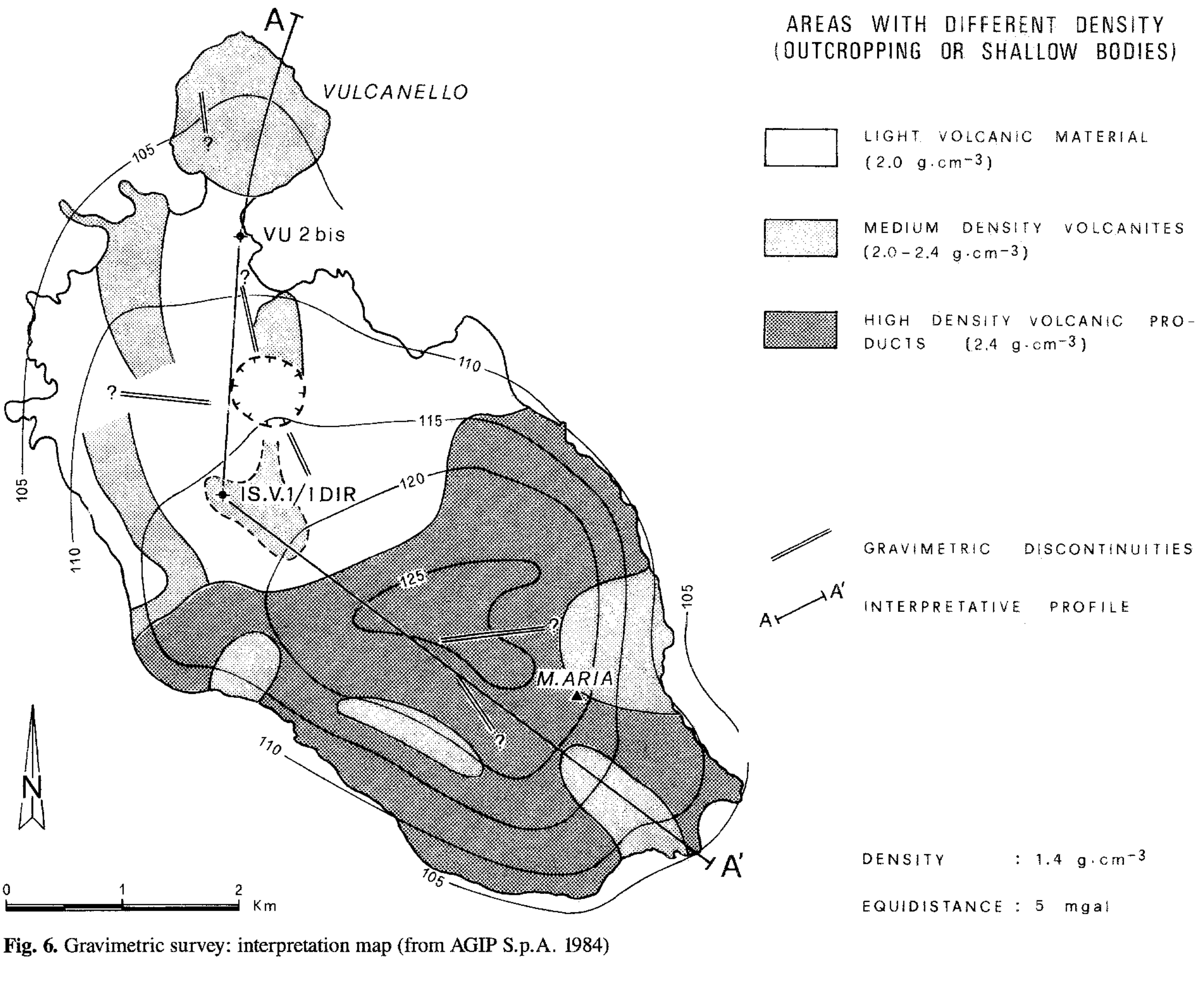

Fig. 6. Gravimetric survey: interpretation map (from AGIP S.p.A. 1984)

ever, is almost always completely altered into an aggregate of calcite, chlorite (penninite), pyrite and limonite. The vein rock is a leuco-monzogabbro, and is interpreted as a steeply inclined dyke originating from the main intrusion.

The recrystallized lava clasts display a porphyritic holocrystalline texture, with plagioclase and pyroxene phenocrysts in a groundmass consisting of granoblasts of plagioclase (which is prevailing) and K-feldspar and of pyroxene granules, with accessory magnetite and apatite. The plagioclase phenocrysts have an irregular, lobate more albitic (andesine-oligoclase) rim, irregular twinning and spotted extinction. The few reliable compositions obtained from twinning gave An_{60} LT. The idiomorphic pyroxene is fractured but more frequently broken down into granules. Values of $2V_Z$=56–62° were determined (augite?). In some clasts the mineral is almost entirely replaced by chlorite and magnetite granules, and sometimes also by calcite, small scales of biotite and pyrite.

The brecciated lava in the lower part of the core is strongly altered. Sometimes only the plagioclase in pheno- and microphenocrysts (An_{60-65} LT) and the magnetite of the primary mineral assemblage are preserved. The chemical analysis of a selected fragment of recrystallized lava (sample 4) is reported in Table 1. Plotted on an R_1R_2 diagram such lava falls within the range of the olivine basalts (Fig. 5). Of the island's volcanic rocks, only the

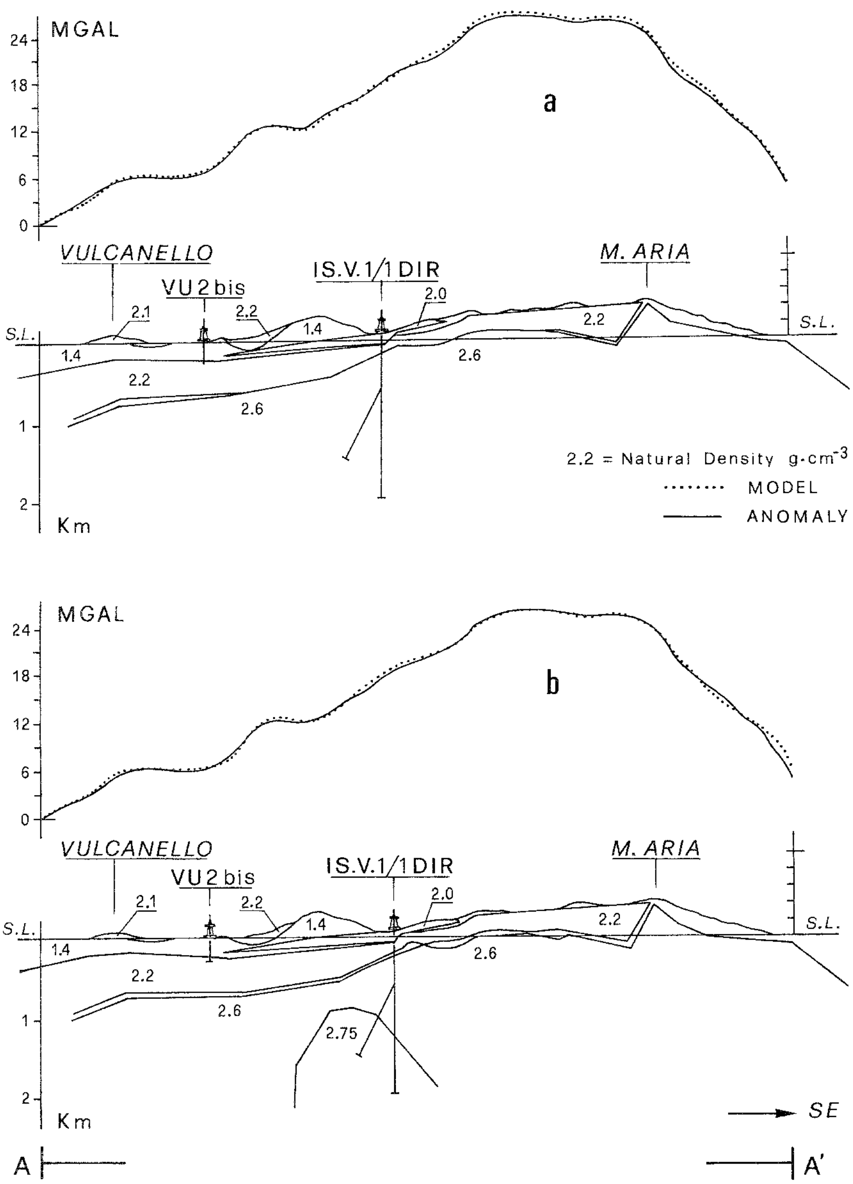

Fig. 7a and b. Gravimetric survey: interpretative profiles. **a** in absence of the intrusive body; **b** in presence of such a body closer to the surface towards the north lavas and dykes of South Vulcano (phenocrysts An_{55-65}) and the scoriae of La Sommata and Quadrara show comparable composition. The recrystallized lava has been metamorphosed by contact with the monzogabbroic intrusion and is thought to originate from the South Vulcano centre.

Geophysical data

Since the northwards deviated well (1DIR) encountered the top of plutonic rock at a shallower depth, and taking into account the thermometric data (gradient increase and trend of the isotherms), the monzogabbroic body may get closer to the surface in a northwards direction. Density measurements on the drill cores show that there is insufficient variation to allow the various lithotypes to be distinguished by gravimetry. The models obtained by using the regional gravimetric data (AGIP S.p.A. 1984) confirm such a limitation.

Figure 6 shows a gravimetric map of the island of Vulcano, and Fig. 7 gives a cross-section A–A′ passing through Vulcanello, Well VU 2bis (AGIP's drilling, 1952–1953), and well IS.V.1/DIR ("Joint Venture" AGIP–EMS–ENEL, 1983–1984) to Mt. Aria. The presence or absence of the intrusion does not make any significant difference to modelling of the gravity anomaly.

As to the extent of the monzogabbro, a model may be assumed on the basis of the results of the regional aeromagnetic survey carried out on most Aeolian islands (AGIP S.p.A. 1982). The magnetometric map (Fig. 8) shows a marked positive anomaly in the stretch of sea to the west of the Mt. Lentìa centre. Qualitative preliminary evaluations suggest that the top of the body causing the anomaly can be located at a depth of approximately 1000 m.

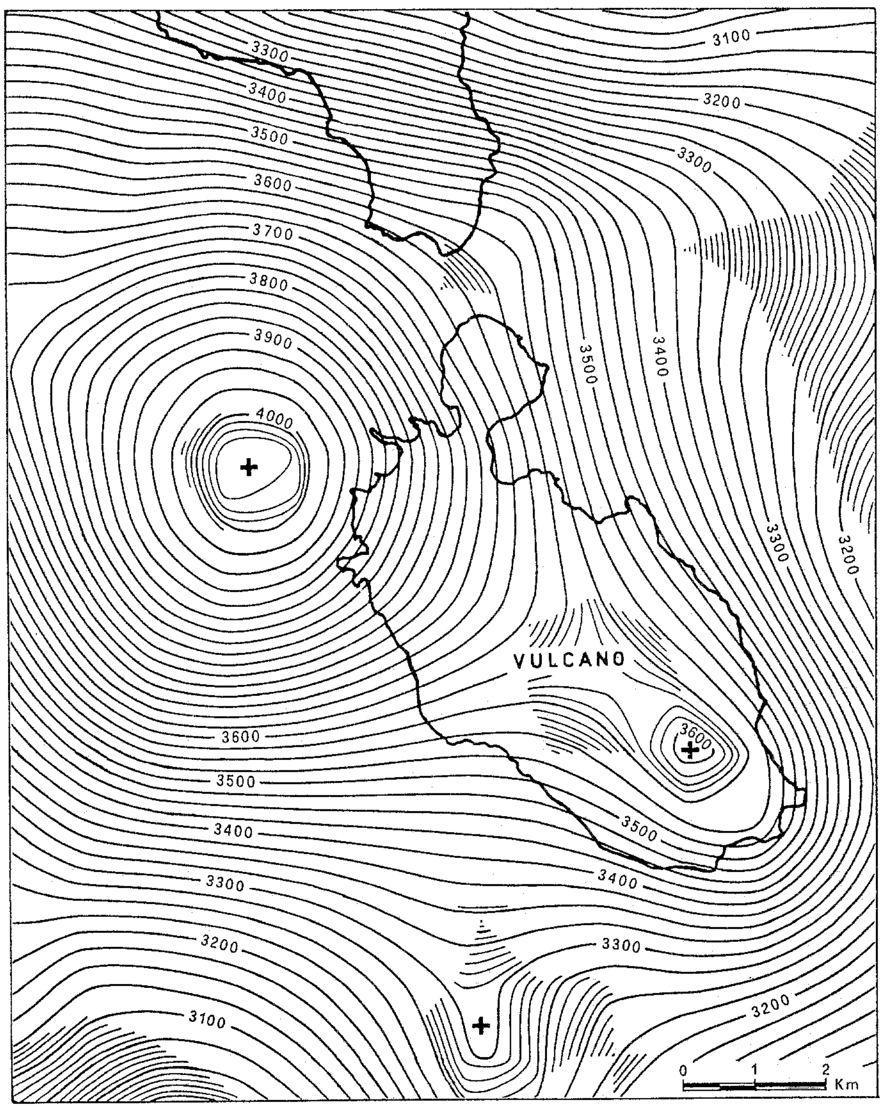

Fig. 8. Aeromagnetic survey: residual magnetic field reduced to the pole (from AGIP S.p.A. 1982)

A less important relative maximum, undoubtedly caused by the lavas of South Vulcano, is found in the area of Caldera del Piano.

The measurements of magnetic susceptibility taken on the core samples of the monzogabbroic intrusion supply very high values, higher than those of the enclosing lavas. Thus, an association between the aforesaid strong magnetic anomaly and the pluton, a marginal zone of which has been penetrated by well IS.V.1/1DIR, appears to be plausible.

Discussion

The rapid increase in temperature in the intrusion to over 400 °C at the bottom of the well is striking. It is possible that a magma body may lie only a few hundred metres below the bottom of the drill-hole, considering the steep thermal gradient.

The age of the intrusion is certainly very recent with evidence of contact metamorphism of lava of the South Vulcano centre. We suspect that the intrusion occurred before the multiple collapse of the Caldera del Piano. There is no sign of fragments or inclusions in the volcanic rocks of the Lentìa, Fossa di Vulcano and Vulcanello centres. However, fragments of monzogabbro are found in a 1 m thick massive pyroclastic (pyroclastic flow?) deposit underlying the welded scoria blanket of Mt. Saraceno, which formed during the collapse of the Caldera del Piano.

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