Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Structural Control of Volcanism at Mount Etna

G. W. Grindley

Phil. Trans. R. Soc. Lond. A 1973 **274**, 165-175
doi: 10.1098/rsta.1973.0037

Email alerting service

Receive free email alerts when new articles cite this article - sign up in the box at the top right-hand corner of the article or click **here**

To subscribe to *Phil. Trans. R. Soc. Lond. A* go to: **http://rsta.royalsocietypublishing.org/subscriptions**

This journal is © 1973 The Royal Society

Downloaded from rsta.royalsocietypublishing.org

Phil. Trans. R. Soc. Lond. A. **274**, 165–175 (1973) [165]
Printed in Great Britain

Structural control of volcanism at Mount Etna

By G. W. Grindley
N.Z. Geological Survey, Lower Hutt, New Zealand

An account is given of the neotectonic development of the Etna volcano in relation to surrounding tectonic regions of Sicily, the Tyrrhenian Sea and southern Italy. The activity of Mt Etna and the earlier Iblean volcano are related to the opening and subsidence of the Tyrrhenian basin since the middle Pliocene. With respect to the Corsica–Sardinia continental block, both the Aeolian volcanic arc and Calabrian outer arc are migrating ESE at about 2–3 cm/year, and subducting oceanic lithosphere of the Ionian basin. Although Mt Etna lies in front of the Aeolian arc in what is normally a non-volcanic (compressional) region, rates of arc migration are sufficiently rapid to allow crustal dilatation normal to the Calabrian arc at the present day, even although it is being rapidly uplifted at a rate of 1 mm/year. Mt Etna is located on the west side of the Messina fault where it is intersected by ENE trending sinistral strike-slip faults on the north side of the Sicilian fore deep that link its volcanic activity with volcanism at many centres in the Sicily Channel. Monitoring of recent earth movements in the Mt Etna region by retriangulation, geodimeter lines, tiltmeters and tide gauges would provide a measure of the secular strain pattern and in time give warning of crustal extension, volcanotectonic doming and lava eruption.

Tyrrhenian orogen

From Lower Miocene times onwards, the Sicilian–Calabrian arc was built up by successive emplacement of thrust sheets, gravitational glide nappes and olistostromes from an orogenic belt that rose in the present site of the Tyrrhenian Sea. The axis of orogenic uplift is marked by a major positive Bouguer gravity anomaly between 150 and 250×10^{-5} m/s^2 (mGal) trending WNW from near Stromboli to beyond the Vavilov sea mount (Morelli 1970). The thrust masses include Hercynian basement gneiss and granite; Upper Palaeozoic greywacke, phyllite, limestone and ophiolitic rocks; Lower Triassic phyllites; Upper Triassic evaporites; Mesozoic carbonates; Upper Jurassic ophiolites and radiolarites; Cretaceous-Lower Miocene flysch, clays and marls (Caire, Glangeaud & Grandjacquet 1960; Caire 1970; Burton 1971; Ogniben 1969, 1970). Glaucophane-lawsonite schists, mylonites and augen gneisses outcropping along the north Calabrian coast either side of the Sangineto fault are typical products of intense high P–low T deformation and metamorphism of late Palaeozoic basement rocks during the Hercynian orogeny and the late Eocene phase of the Alpine orogeny in the Tyrrhenian region, as shown by recent radiometric dating (Borsi & Dubois 1968). Nappes were mainly emplaced in Calabria in the late Oligocene and early Miocene, were refolded in the Middle Miocene together with autochthonous Oligocene and Lower Miocene molasse and further deformed in the late Miocene and early Pliocene (Burton 1971, p. 370). Late Miocene evaporites were deposited in the Tyrrhenian basin at the climax of the orogeny immediately prior to its subsidence (Selli & Fabbri 1971).

In Sicily, the earliest nappe movements were Hercynian in age (Truillet 1970; Duée 1970) when the Peloritani basement phyllites were overfolded in a huge fold nappe and the core intruded syntectonically by granitic gneiss. The inverted limb of this nappe (shown by inverted metamorphic zonation) was overlain unconformably by Permian–Triassic conglomerate and sandstone ('Verrucano') and Mesozoic carbonates. In the Eocene phase of the Alpine orogeny, further southward overthrusting took place with incorporation of slices of Mesozoic carbonates

The Royal Society is collaborating with JSTOR to digitize, preserve, and extend access to
Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences.
www.jstor.org

Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

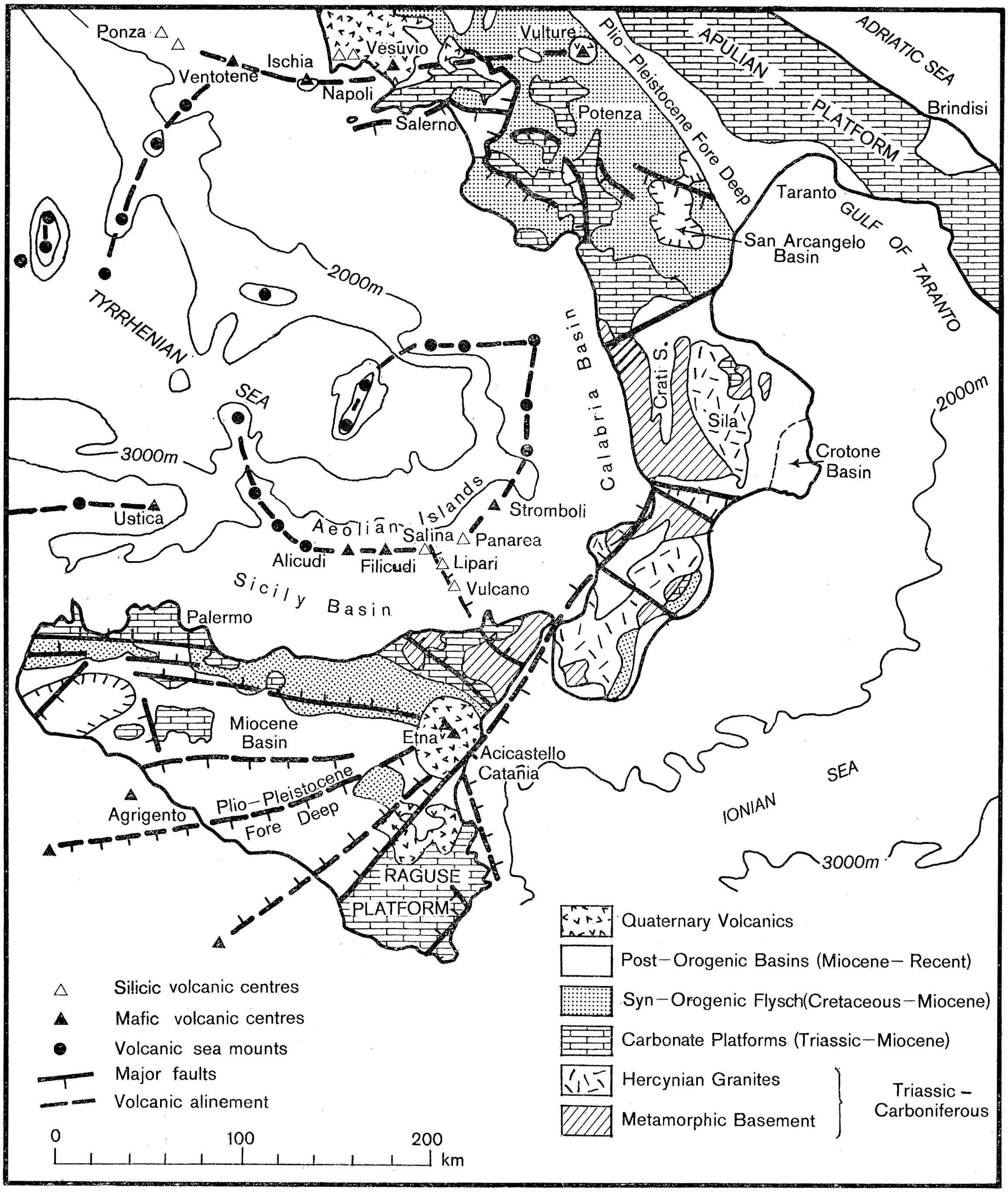

FIGURE 1. Generalized geological map of southern Italy and Sicily showing major structures and volcanoes. Land geology from International Tectonic Map of Europe (1964). Submarine geology from Morelli (1970).

and Eocene flysch into the basement. Oligo-Miocene molasse was deposited unconformably on the metamorphic terrain and the Numidian flysch was deposited farther to the south. In the Middle Miocene, a further orogenic paroxysm took place with southward thrusting of basement and limestone nappes over the external flysch basin (Duée 1970). In the late Miocene, the 'argille scagliose' nappes were emplaced over the preceding nappes, probably from an internal flysch basin to the north in the Tyrrhenian sea region. Resedimentation of olistostromes

Downloaded from rsta.royalsocietypublishing.org

and olistoliths on a grand scale took place at intervals throughout the Pliocene and early Pleistocene into the Sicilian (Caltanisetta) Basin or fore deep in the south of Sicily as the northern ranges were uplifted. The chief tectonic phases were in the Lower Pliocene, mid-Pliocene and Lower Pleistocene (Roda 1967). Uplift of the northern flank of the Sicilian fore deep started in the mid-Pliocene and still continues. It is still in isostatic imbalance as shown by the negative Bouguer gravity anomaly of over 80×10^{-5} m/s^2.

From the movement directions of nappes, the axes of compressional folds and the sense of displacement of a few strike slip faults (see, for example, Ogniben 1969) it is possible to estimate maximum shortening directions for the Miocene and Pliocene phases of the Alpine orogeny in the Calabro–Sicilian region. A consistently simple pattern emerges, symmetric with respect to the Tyrrhenian axis of mantle uplift inferred from the gravity anomaly. From the axis of uplift, lines of maximum shortening fan out normal to the Sicilian-Calabrian arc or fold belt (figure 2). In the Tyrrhenian basin itself, arcuate ridges outlined by the bathymetric chart of Morelli (1970) are consistent with the same pattern and probably represent subsided portions of the orogenic belt (Selli & Fabbri 1971). These arcuate anticlinal ridges and intervening synclinal troughs are also shown on the time-isopachous contour map of the Plio-Pleistocene soft sedimentary cover deposited on the folded terrain after it subsided below sea level (Finetti, Morelli & Zarudski 1970, p. 335). A thin sedimentary cover blankets the ridges and thicker sediments fill the synclinal troughs. Confirmation of the existence of metamorphic and indurated sedimentary rocks below the Tyrrhenian Sea has been obtained by reflexion seismic profiling (Finetti *et al.* 1970) and by direct sampling of rocks from steep submarine scarps (Heezen, Gray, Segre & Zarudski 1971). The phyllite-limestone sequence described by Heezen *et al.* (1971) appears to be very similar to the Cetraro unit of Lower Triassic phyllites overlain by Upper Triassic limestones and dolomites, exposed on the Calabrian coast south of the Sangineto fault (Caire *et al.* 1960).

The origin of the Sangineto, Catanzaro and other major faults transverse to the Appenine structures appears to be related to bending and stretching of the Calabrian–Sicilian arc during late Cenozoic orogenic deformation, although Caire *et al.* (1960) apparently regard them as more ancient rift-zones related to the emplacement of the Upper Jurassic ophiolites. If this view is correct, they must certainly have been reactivated as normal faults during the Cenozoic, as they cross the Calabrian folds almost at right angles. Other important faults which may have been generated at this time include the Lipari–Vulcano line, the faulted eastern edge of the Raguse platform in Siciliy, and the major fault through the straits of Messina. The Messina fault would necessarily have originated as a sinistral strike-slip fault as proposed by Ogniben (1969). Another lineament of possibly the same age is the Ponza–Ventotene–Ischia volcanic line west of Naples, also shown as a sinistral strike-slip fault.

The only volcanism associated with the Tyrrhenian orogenesis was the earliest activity of the Iblean volcano along the NW edge of the Raguse platform (Cristofolini 1967*b*; Rittmann 1964) which apparently commenced in the early Pliocene. Pillow lavas and hyaloclastites were the chief products (Rittmann 1962; Pichler 1970).

Downloaded from rsta.royalsocietypublishing.org

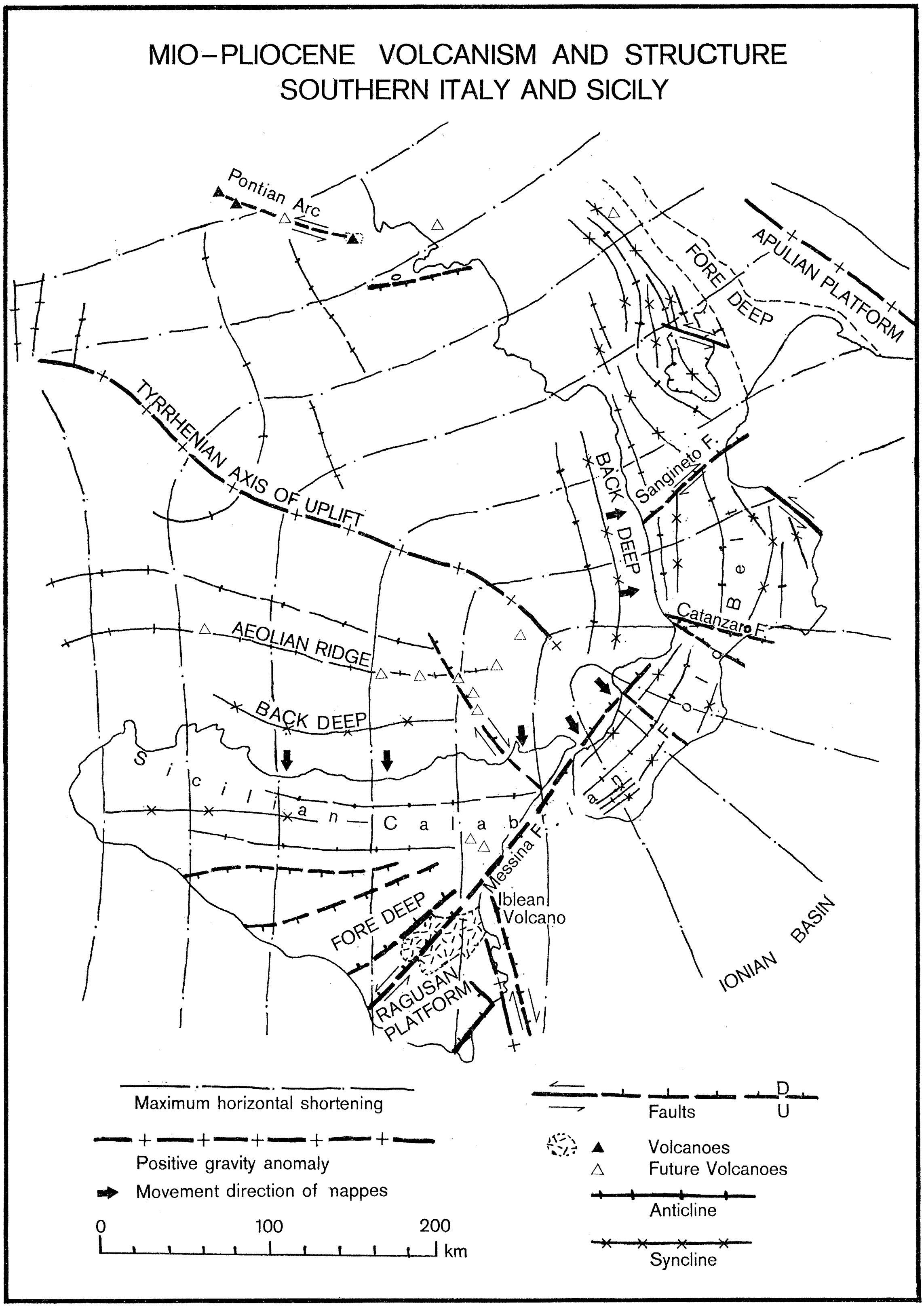

FIGURE 2. Tectonic sketch map of southern Italy and Sicily during Tyrrhenian uplift and Calabrian–Sicilian folding (late Miocene–early Pliocene). Axis of mantle and crustal uplift marked by positive Bouguer anomaly (150–250×10^{-5} m/s^2 (mGal)). Structures mainly from Ogniben (1969, 1970), Caire (1970), Burton (1971) and 1:2500000 International Tectonic Map of Europe (1964). No allowance is made for later extension in Tyrrhenian basin.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

Tyrrhenian subsidence

From Middle Pliocene times onwards, the Tyrrhenian orogen with its continental crust reduced by subaerial and tectonic erosion (landsliding and gravitational glide nappes) to less than 5 km subsided continuously to between 3000 and 4000 m. Subsidence was accompanied by downwarping of the continental margins of Italy and Sicily, by extension in a WNW direction behind the active Aeolian island arc and subduction zone, and by widespread volcanism both on the floor of the Tyrrhenian Sea and around its margins (Morelli 1970; Selli & Fabbri 1971). Rates of subsidence averaging 1 mm/year can be estimated since the mid-Pliocene (4 Ma) and this rate is quite comparable with the rate of uplift of the Calabro–Sicilian arc in Calabria and western Sicily (Burton 1964; personal observation). Within the Tyrrhenian basin, mafic volcanism broke out at many centres as shown by large residual magnetic anomalies associated with sea mounts and both linear and arcuate ridges (Finetti *et al.* 1970, p. 335). The alinement of linear magnetic ridges such as Marsili, Vavilov and Magnaghi sea mounts in a NNE direction, considered to be along normal faults, suggests WNW extension parallel to the axis of the Bouguer gravity anomaly (Selli & Fabbri 1971, p. 590). From the seismic profile MS–1 (Finetti *et al.* 1970, pp. 332–3) it is possible to gain an estimate of the total extension, since this profile crosses the Tyrrhenian basin in a WNW direction. In the western part of the basin, between Sardinia and the Vavilov sea mount, the extension due to normal faulting is balanced by compressional folding and reverse faulting. In the eastern part of the basin, apparent extension measured from the seismic profiles averages 30% over a total distance of 400 km, a net extension approaching 120 km. This extension is directly related to the subsidence of the Tyrrhenian basin and has probably taken place over the last 4–6 Ma at an average rate of 2–3 cm/year.

Seismicity

Both shallow and deep focus seismicity are known from the Sicilian–Calabrian arc and from the Tyrrhenian Sea. A map showing epicentres for the last 70 years was compiled by Ritsema (1970) and reproduced by Morelli (1970, p. 290). Shallow focus seismicity characterizes the Sicilian–Calabrian fold belt from Palermo to Potenza. Fault-plane solutions published by Ritsema (1969, p. 117) indicate strike-slip movements with maximum shortening parallel to the arc in Calabria and oblique to the arc in Sicily. In western and southern Sicily and in the remainder of Italy, fault-plane solutions indicate normal faulting parallel to the Appenines in Italy and in a NE direction oblique to the arc through Sicily (Ritsema 1969, p. 117). Lines of maximum shortening (figure 3) consistent with the few published fault-plane solutions outline a gentle arc parallel to the Appenines and Calabrian mountains and trending obliquely southwest across Sicily. This pattern is also in harmony with extension of the southern Tyrrhenian basin in a WNW direction as outlined above; the strain pattern is considered to relate to the post-orogenic period in southern Italy and Sicily covering the subsidence of the Tyrrhenian basin, the uplift of the Sicilian–Calabrian arc and the widespread Plio-Quaternary volcanism, i.e. the last 4 to 6 Ma since the Lower Pliocene.

Deep-focus seismicity characterizes a small triangular area in the SE Tyrrhenian basin, on the concave side of the Sicilian–Calabrian arc of shallow seismicity. Epicentres are mainly between 200 and 350 km deep, rarely extending below 400 km, and with a 150 km aseismic gap between them and the crustal earthquakes in Calabria and Sicily. The active volcanoes of

Downloaded from rsta.royalsocietypublishing.org

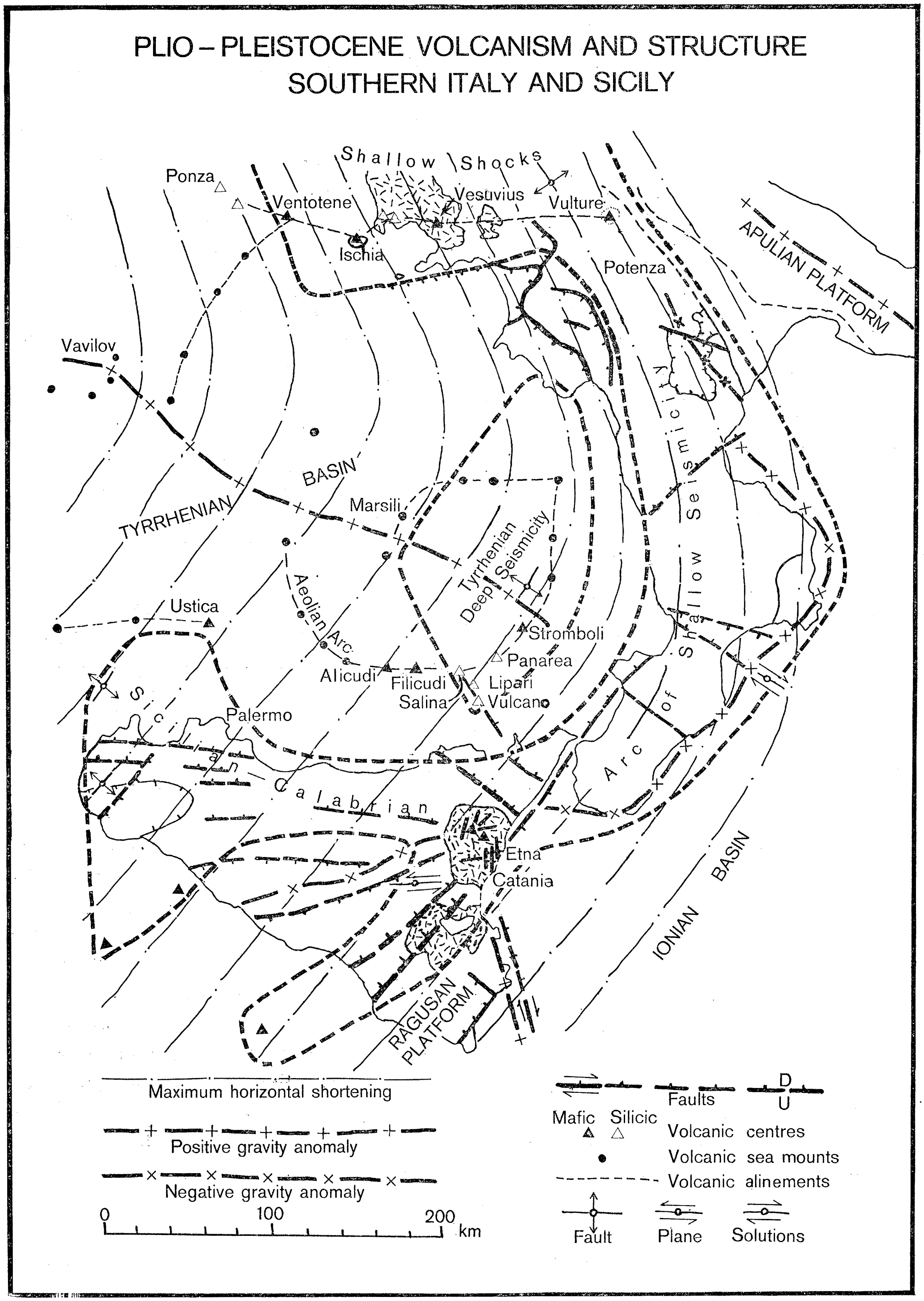

FIGURE 3. Tectonic sketch map of southern Italy and Sicily during Tyrrhenian subsidence and Calabrian–Sicilian uplift (late Pliocene–present). Tyrrhenian subsidence is marked by intense submarine volcanism on NNE rifts symmetric with gravity anomaly, and outer margin of Sicilian–Calabrian arc by negative Bouguer anomalies ($50–80 \times 10^{-5}$ m/s^2). Seismic zonation and fault plane solutions after Ritsema (1969).

Downloaded from rsta.royalsocietypublishing.org

Stromboli and Vulcano, recently active volcanoes of Lipari and Salina, and several sea mounts are directly above the zone of deep foci, as in circum-Pacific island arcs, with which the Aeolian arc is often compared (see, for example, Peterschmitt 1956; Gutenberg & Richter 1954). According to modern plate tectonic theory, both the deep focus seismicity and the shallow-focus seismicity can be related to a subduction zone, dipping to the WNW at approximately 50° (Ritsema 1970; Morelli 1970, p. 290). Such an interpretation requires underthrusting of a lithospheric slab 50 km thick from the Ionian oceanic basin to the southeast, below the narrow continental Sicilian–Calabrian arc. A negative gravity anomaly is present on the Ionian side of the arc with Bouguer anomalies approaching 50×10^{-5} m/s² (figure 3). There does not appear to be any sign of a physiographic trench, although water depths approach 3000 m within 100 km of the coast (figure 1). Ritsema (1969, p. 116) has given fault-plane solutions for deep foci below the Tyrrhenian Sea, showing the maximum pressure stress dipping at about 60° towards WNW with the principle tension stress dipping 30° towards ESE. These solutions are in accord with compression directed down the underthrust slab by oceanic lithosphere from the Ionian basin. This model is in accord with Quaternary uplift of the Sicilian–Calabrian arc where the migrating continental crust rides over the underthrusting oceanic crust. Although the descending slab is under compression, the overthrust crustal slab is being compressed parallel to its length and is still extending in the direction of motion.

Gravity and crustal layering

The huge Bouguer positive gravity anomaly in the Tyrrhenian basin (Vecchia 1955; Morelli 1970) occupies the entire subsided region between Italy, Sicily and Sardinia. Although complex in detail, the gravity contours generally trend parallel to the coast lines, the actual coast being closely followed by the $+50 \times 10^{-5}$ m/s² contour, the 1000 m isobath by the 100×10^{-5} m/s² contour, the 2000 m isobath by the 150×10^{-5} m/s² contour and the 3000 m isobath by the 200×10^{-5} m/s² contour, i.e. approximately 50×10^{-5} m/s² rise in gravity for every 1000 m of subsidence. The gravity anomaly is most easily attributed to updoming of the mantle, thinning of the continental crust by tectonic erosion and thickening of the underlying oceanic crust while under regional compression during the Tyrrhenian orogeny. With relaxation of compression during the mid-Pliocene, the thin granitic crust underlain by a thick dense intermediate crust sank isostatically to its appropriate level. Seismic refraction profiles in the centre of the Tyrrhenian basin show between 2 and 3 km of granitic crust and sediments underlain by an intermediate layer of unknown thickness with seismic velocities of 6.9 to 7.5 km/s (Fahlquist & Hersey 1969). Russian results around Vavilov sea mount give more details (Moskalenko 1967):

0.3 to 1.2 km of v = 1.8–2.3 km/s (Plio-Quaternary),
0.4 to 1.2 km of v = 4.0 km/s (Miocene),
1.8 to 2.4 km of v = 5.0 km/s (basement).

The maximum thickness of granitic crust appears to be 5 km. From the Tyrrhenian basin, the thickness of the continental granitic crust increases with the fall in Bouguer gravity values to almost 20 km in Italy and Sicily and the M-discontinuity appears at 30 to 35 km. Even greater crustal thicknesses are measured below the Apulian platform and Adriatic Sea where the M-discontinuity reaches 45 km (Ritsema 1969). Below Mt Etna, the M-discontinuity is at 20 to 25 km and a low velocity zone in the upper mantle at the unusually shallow depth between 32 and 36 km is believed to be the source for the intense volcanism (Cassinis *et al.* 1969).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Downloaded from rsta.royalsocietypublishing.org

Structure and volcanism

Mt Etna is controlled by NNE, ENE and NE fissures (Rittmann 1964; Ogniben 1966; Cristofolini 1967*a*; Romano 1971), symmetric with a NE shortening direction (figure 3). The large normal faults trending NE along the edge of the Ragusan platform are active (Vecchia 1955; Peterschmitt 1956) and join with the Messina fault (Ogniben 1969) an active normal fault striking NE through the Straits of Messina. The 1783 Calabrian earthquakes and the 1908 Messina earthquakes, among many others, are reminders that this fault is indeed very active (Davison 1936). Mt Etna is also being raised at the rate of 1 mm a year on the northern flank of the isostatically uncompensated Sicilian fore deep and probably owes its location to the intersection of this rising axis with strike-slip and normal faults that produce extensive fissuring and allow the rise of alkaline basalt magma from the low-velocity layer in the upper mantle. The ENE faults that cross the northern flank of the Sicilian fore deep are sinistral strike-slip faults, as shown by a fault-plane solution a few kilometres west of Mt Etna (Ritsema 1969; and figure 3). They link Mt Etna with the active volcanism of the Sicilian Channel between Sicily and North Africa. About 14 active or dormant volcanic centres are known from this area of which the most well known is the island of Pantellaria (localities given in Imbo 1965). They appear to lie along NNE to ENE lines and to be thus controlled by the same stress field as is Mt Etna.

Despite their close proximity to the Aeolian island arc there appears to be no direct relationship with lithosphere underthrusting. Only shallow seismicity is associated with the Sicilian channel volcanoes and Mt Etna. All are alkaline or peralkaline lavas derived directly from the upper mantle as is shown by their $^{87}Sr/^{86}Sr$ ratios being low (averaging 0.705) (Pichler 1970; Barberi, Borsi, Ferrara & Innocenti 1969) and by their lack of crustal contamination. In contrast, the Aeolian volcanoes (Lipari, Stromboli, Salina, Vulcano, etc.) are calc-alkaline to alkaline and are strongly contaminated with crustal material as shown by xenoliths and xenocrysts of metamorphic rocks and minerals (Pichler 1967; von Honnorez & Keller 1968). The Aeolian volcanoes, besides being in part of anatectic (crustal) origin, are also arranged in an arc-shaped festoon above a small zone of intermediate depth earthquakes, as in typical circum-Pacific island arcs. Due to crustal contamination, leading to strong enrichment in alkalis, it is not possible to establish by potash-silica ratios, the depths to the Benioff Zone (Hatherton & Dickinson 1968). However, the reality of the subduction process is clearly shown by the deep seismicity with appropriate down-dip compressional vectors, and by the rapid extension that has taken place in the behind-the-arc Tyrrhenian basin (cf. Karig 1971, 1972).

A solution involving a consideration of the late Cenozoic plate movements in the western Mediterranean is obviously demanded in order to explain the peculiar structural position of Mt Etna. Not only does Mt Etna lie in front of the Aeolian arc and subduction zone, in what is normally a non-volcanic (compressional) region, it is also taking part in the folding process at the same time as magmas are being produced. It is a curious enigma requiring a most favourable conjunction of suitable tectonic elements to permit extensive crustal fissuring and the growth of such a large volcano in such a short interval of time at this locality. A close temporal relation with subduction seems likely from the timing of the inception of volcanism – mid-Pleistocene (Sicilian) at Mt Etna (Rittmann 1964) and Sicilian–Milazzian in the Aeolian arc (Pichler 1968).

Downloaded from rsta.royalsocietypublishing.org

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Relation of Mount Etna to subduction

It has been shown that the Calabrian outer arc, the Aeolian inner arc, and the Tyrrhenian basin are actively migrating in an ESE direction and subducting oceanic lithosphere in the Ionian oceanic basin. The major fault controlling Mt Etna volcanism, the Messina fault, extends NE into the Calabrian arc, where it has been responsible for many recent damaging earthquakes. To the NE the Messina fault is cut off by the NW striking Catanzaro fault, a dextral strike-slip fault, as shown by a recent fault-plane solution (Ritsema 1969). To the SW the Messina fault extends out into the Sicily Channel and is probably cut off by a NW striking strike–slip fault along the Sicily Channel near the volcano of Pantellaria. Between these two faults the Messina fault is rotating counter-clockwise and migrating ESE along with adjacent parts of Sicily and Calabria. It appears likely then that Mt Etna is controlled by at least five tectonic factors:

(1) The Messina fault and parallel fractures to the west.

(2) A number of sinistral strike slip shears extending WSW along the northern flank of the Sicilian fore deep to the volcanic field in the Sicily Channel.

(3) A general migration of the Calabrian–Sicilian arc in an ESE direction with subduction of oceanic crust.

(4) The low velocity channel in the upper mantle at 32 to 36 km.

(5) The active crustal uplift of 1 mm/year can facilitate magma generation provided the crust is not under compression.

Neotectonic movements and volcanic prediction

Mt Etna is one of the most consistently active volcanoes on Earth in the historic period (Rittmann 1964; Pichler 1970; Cristofolini 1967*a*; Huntingdon 1972). It seems highly probable, considering its tectonic situation, that the neotectonic crustal movements in the region of Mt Etna are of sufficient magnitude to be monitored with modern geodetic instruments, and so permit estimation of secular rates of neotectonic movement. If, as seems likely, volcanism and neotectonic movements are closely inter-related, monitoring of the movements should be an additional technique in unravelling the volcano-tectonic history of the Mt Etna region, and a potential safeguard for those unfortunate enough to have seen homes and farms destroyed without warning in recent catastrophic eruptions. It is suggested, therefore, that measurements be made of:

(1) The rate of uplift of Mt Etna and surroundings due to tectonic (not volcanic) activity by tide-gauges.

(2) The rate of extension in an ESE direction across Etna volcano and the Messina fault by geodimeter lines.

(3) Retriangulation of the old and installation of new survey stations on Etna volcano and the surrounding non-volcanic region to determine the secular strain pattern.

(4) Installation of tiltmeters at suitable sites on the volcano to provide adequate immediate warning of volcano-tectonic doming and eruption of lava.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Downloaded from rsta.royalsocietypublishing.org

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

References (Grindley)

Barberi, F., Borsi, S., Ferrara, G. & Innocenti, F. 1969 Strontium isotopic composition of some recent basic volcanites of the Southern Tyrrhenian Sea and Sicily Channel. *Contr. Miner. Petrol.* **23**, 157–172.

Borsi, S. & Dubois, G. 1968 Donnees geochronologiques sur l'histoire hercynienne et alpin de la Calabre centrale. *C. r. hebd. Séanc. Acad. Sci., Paris* **266**, 72–75.

Burton, A. N. 1964 Marine levels in South Italy. *Nature, Lond.* **203**, 1060.

Burton, A. N. 1971 Note on the Alpine orogeny in Calabria, southern Italy. *Q. Jl geol. Soc. Lond.* **503** 126 (3), 369–382.

Caire, A. 1970 Sicily in its Mediterranean setting. *Geology and history of Sicily. Pet. Expl Soc. Libya 12th Field Conf.* (ed. W. Alvarez and K. H. A. Gohrbandt). Tripoli 1970.

Caire, A., Glangeaud, L. & Grandjacquet, C. 1960 Les grands traits structureaux et l'evolution du territoire Calabro-Sicilien (Italie meridionale). *Bull. Soc. geol. Fr.* **7** (II), 915–938.

Cassinis, R., Finetti, I., Giese, P., Morelli, C., Steinmetz, L. & Vecchia, O. 1969 Deep seismic refraction research on Sicily. *Boll. geofis. Teor. applic.* **11**, 43–44, 140–160.

Cristofolini, R. 1967*a* La successione dell'attivita vulcanica sulle pendici sud-occidentali dell'Etna. *Atti Accad. gioenia Sci. nat.* (Suppl. Sci. Geol. Ser. 6), **18**, 283–294.

Cristofolini, R. 1967*b* Le vulcaniti plio-pleistoceniche al margine settentrionale dell'Altipiano Ibleo. *Atti Accad. gioenia Sci. nat.* (Suppl. Sci. Geol. Ser. 6) **18**, 265–270.

Davison, C. 1936 *Great earthquakes.* London: Thos. Murby and Co.

Duée, G. 1970 The geology of the Nebrodi Mountains of Sicily. *Geology and history of Sicily*, pp. 187–200. *Pet. Expl Soc. Libya 12th Field Conf.* (ed. W. Alvarez and K. H. A. Gohrbandt). Tripoli 1970.

Fahlquist, D. A. & Hersey, J. B. 1969 Seismic refraction measurements in the western Mediterranean Sea. *Bull. Inst. océanogr. Monaco* **67**, 1386.

Finetti, I., Morelli, C. & Zarudski, E. 1970 Reflection seismic study of the Tyrrhenian Sea. *Bull. geofis. Teor. Applic.* **12** (N 48), 311–346.

Gutenberg, B. & Richter, C. F. 1954 *Seismicity of the Earth and associated phenomena.* Princeton, N.J.: Princeton University Press.

Hatherton, T. & Dickinson, W. R. 1968 Andesitic volcanism and seismicity in New Zealand. *J. geophys. Res.* **73**, 4615–4619.

Heezen, B. C., Gray, C., Segre, A. G. & Zarudski, E. F. K. 1971 Evidence of foundered continental crust beneath the central Tyrrhenian Sea. *Nature, Lond.* **229**, 327–329.

von Honnorez, J. & Keller, J. 1968 Xenolithe in vulkanischen Gesteinen der Aolischen Inseln (Sizilien). *Geol. Rdsch.* **57**, 719–736.

Huntingdon, A. T. 1972 The eruption of Mt Etna 1971. *Sci. Prog. Oxf.* **60**, 107–119.

Imbo, G. 1965 Catalogue of the active volcanoes of the World including Solfatara fields. Part 18 Italy. *Int. Ass. Volcan.* 70 pp. Rome.

Karig, D. E. 1971 Origin and development of marginal basins in the Western Pacific. *J. geophys. Res.* **76** (11), 2542–2561.

Karig, D. E. 1972 Remnant Arcs. *Bull. geol. Soc. Am.* **83**, 1057–1068.

Morelli, C. 1970 Physiography, gravity and magnetism of the Tyrrhenian Sea. *Boll. geofis. Teor. Applic.* XII (**48**), 275–309.

Moskalenko, V. N. 1967 Structure of the sedimentary cover in the Tyrrhenian Sea interpreted from seismic data. *Izvestia Acad. Nauk SSSR* (ser. Geol.) **6**.

Ogniben, L. 1966 Lineamenti idrogeologici dell'Etna. *Riv. miner. Siciliana* XVII, N**100–102**, 24 pp.

Ogniben, L. 1969 Schema introduttivo alla geologia del confine Calabro-Lucano. *Mem. Soc. Geol. Ital.* **8**, 453–763.

Ogniben, L. 1970 Paleotectonic history of Sicily. *Geology and history of Sicily. Pet. Expl Soc. Libya, 12th Field Conf.* (ed. W. Alvarez and K. H. A. Gohrbandt). Tripoli 1970.

Peterschmitt, E. 1956 Quelques données nouvelles sur les seismes profonds de la mer Tyrrhenienne. *Ann. Geofis.* **9**, 305–334.

Pichler, H. 1967 Neue Erkenntnisse über Art und Genese des Vulkanismus der Aolischen Inseln (Sizilien). *Geol. Rdsch.* **57**, S102–S126.

Pichler, H. 1968 Zur Altersfrage des Vulkanismus des Aolischen Archipels und der Insel Ustica (Sizilien). *Geol. Mitt.* **7**, 299–332, Aachen.

Pichler, H. 1970 Volcanism in eastern Sicily and the Aeolian Islands. *Geology and history of Sicily. Pet. Expl Soc. Libya, 12th Field Conf.* (ed. W. Alvarez and K. H. A. Gohrbandt). Tripoli 1970.

Ritsema, A. R. 1969 Seismic data of the western Mediterranean and the problem of oceanization. *Verhand. Kon. Ned. Geol. Mijn.* XXVI, 105–120. Symposium on the problem of oceanization in the western Mediterranean area. Delft.

Ritsema, A. R. 1970 On plate tectonics in the Mediterranean region. Europ. Seismol. Commission C. R. Luxembourg Meeting.

Downloaded from rsta.royalsocietypublishing.org

Rittmann, A. 1962 *Volcanoes and their activity*. New York: Interscience–Wiley.

Rittmann, A. 1964 Vulkanismus und Tektonik des Aetna. *Geol. Rdsch.* **55**, 788–800.

Roda, C. 1967 I sedimenti plio-pleistocenici nella Sicilie centro-meridionale. *Atti. Accad. gioenia Sci. nat.* (Suppl. Sci. Geol. Ser. 6) **18**, 295–310.

Romano, R. 1971 Tectonic control on magmatic differentiation: an example. *Bull. Volcan.* **34** (4), 823–832.

Selli, R. & Fabbri, A. 1971 The Tyrrhenian deep Pliocene sea. *Accadamea dei Lincei. Rend. Class. Sci. Fis. Mat. Nat.* **8**, L5, 580–592.

Truillet, R. 1970 The geology of the eastern Peloritani Mountains of Sicily. *Geology and history of Sicily*, pp. 171–185. *Pet. Expl Soc. Libya*, 12*th Field Conf.* (ed. W. Alvarez and K. H. A. Gohrbandt). Tripoli 1970.

Vecchia, O. 1955 Le Sicilie e le area circostanti lineamenti, geofisica et geologia profonda. *Bull. geol. Soc. Ital.* **75** (1), 61–87.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES