Stratigraphic approaches and tools in the geological mapping of Mt. Etna Volcano

Stefano BRANCA*, Mauro COLTELLI*,
Paola DEL CARLO*, Gianluca GROPPELLI**,
Gianluca NORINI*** & Giorgio PASQUARE***.

* Istituto Nazionale di Geofisica e Vulcanologia (INGV), Catania, Italia
** Istituto per la Dinamica dei Processi Ambientali, Consiglio Nazionale delle Ricerche (CNR), Milano, Italia
*** Dipartimento di Scienze della Terra "A. Desio", Università di Milano, Milano, Italia

ABSTRACT

This study addresses the stratigraphic methodology adopted for the realisation and representation of a geological map of Mt. Etna. In particular, the example of an area taken from the 625 Acireale Sheet (1:50,000 scale), located on the eastern flank of the volcano, is presented. We discuss the opportunity of integrating different stratigraphic categories, such as lithostratigraphic, synthemic and lithosomatic units, for a better representation on the geological map and for an in-depth knowledge of the structure and geological history of a recent and active central volcano. The significant role of tephrostratigraphy for such a purpose is also outlined. Furthermore, we provide an example of GIS processing of geological data for the purposes of a preliminary lava flow hazard assessment.

AIMS

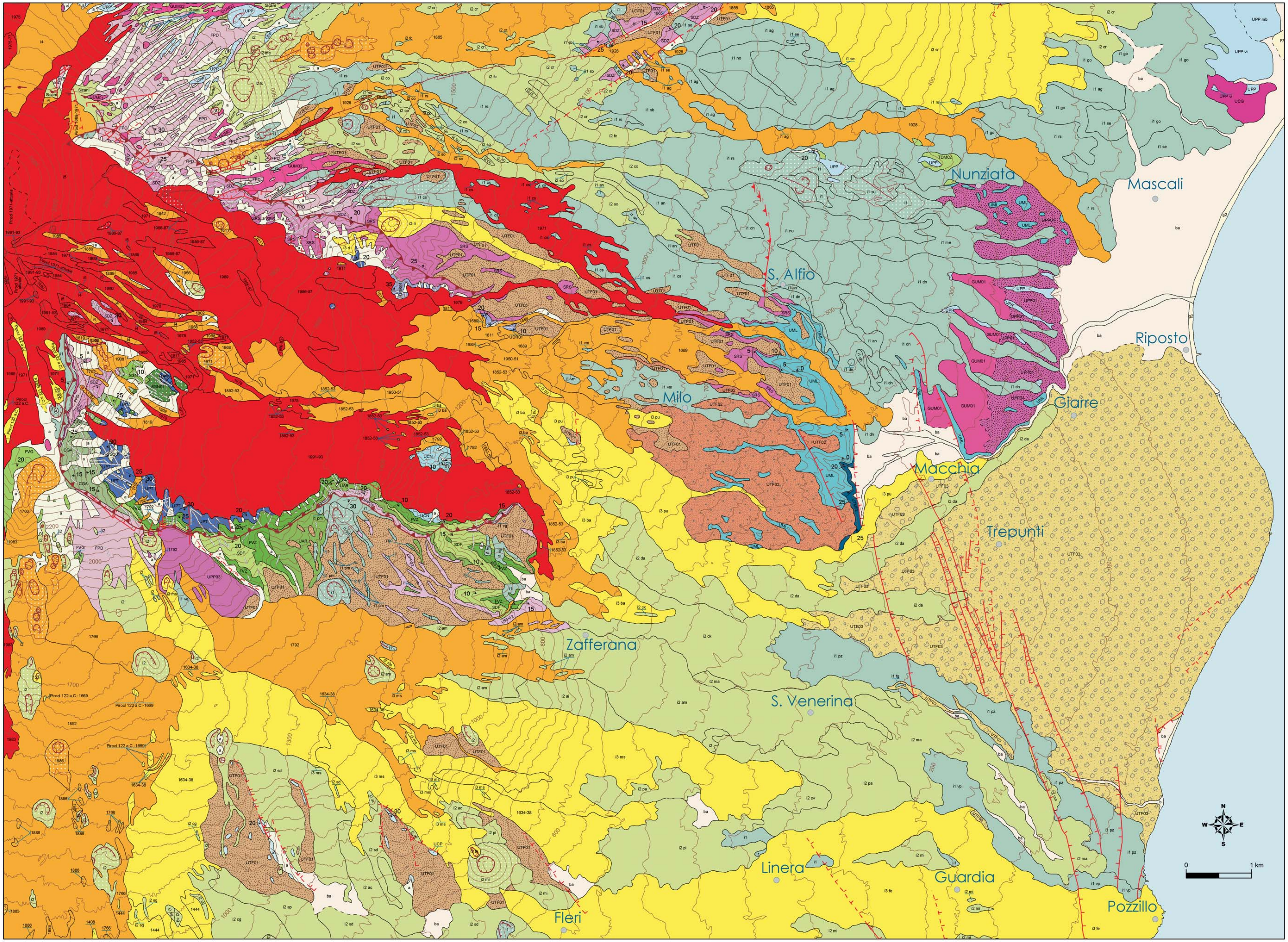
In this work the following elements are discussed:
1) a stratigraphic methodology useful in mapping volcanic areas, based on the contemporaneous use of three different stratigraphic categories (lithostratigraphic, synthemic and lithosomatic units);
2) the use of stratigraphy as an important tool to reconstruct the structural and geological evolution of a recent strato-volcano;
3) the role of explosive activity in a mainly effusive volcano and the importance of tephrostratigraphy;
4) the contribution of geological mapping towards assessing volcanic hazards.

KEY WORDS

Geological map, Volcanoes, Mt. Etna volcano, stratigraphy, lithostratigraphic unit, synthemic unit, lithosomatic unit, tephrostratigraphy, lava flow hazard assessment

RIASSUNTO

Questo lavoro affronta la metodologia stratigrafica adottata per la realizzazione e La rappresentazione di una nuova carta geologica del Monte Etna. In particolare viene presentato un esempio tratto dal Foglio 625 Acireale alla scala 1:50.000, localizzato sul versante orientale del vulcano. Si analizza l'opportunità di integrare differenti unità stratigrafiche, come quelle litostratigrafiche, sintemiche e litosomatiche, allo scopo di una rappresentazione cartografica che possa illustrare compiutamente la complessa struttura e storia geologica di un grande vulcano centrale recente e tuttora attivo. Nella metodologia adottata viene dato anche particolare rilievo all'indagine tefrostratigrafica, fino ad oggi trascurata in un edificio dall'attività prevalentemente effusiva. Viene illustrato inoltre un esempio di elaborazione GIS dei dati geologici, utile per una preliminare valutazione della pericolosità vulcanica da invasione lavica.



GEOLOGICAL MAP OF THE EASTERN FLANK OF MOUNT ETNA

Symbol

- Bedding attitude
- Dike
- Stratigraphic boundary
- Uncertain stratigraphic boundary
- Normal slip fault
- Uncertain or burried normal slip fault
- Normal oblique slip fault
- Reverse oblique slip fault
- Crater rim
- Caldera rim
- Buried caldera rim
- Flank collapse rim
- Eruptive fracture
- Hydrothermal alteration area
- Scoria cone

Fig. 1 - *Geological map of the eastern flank of Mt. Etna Volcano (for the location, see fig. 3)*

ACTUAL AND RECENT CONTINENTAL AND TRANSITIONAL DEPOSITS

Seashore deposits (g2). Gravel deposit with volcanic and sedimentary isometric pebbles.
Slope deposits (a). Volcanic heterometric and heterogeneous angular pebbles in sandy matrix deposited by gravity at the base of deep slopes and fault escarpments.
Present-day alluvial deposit (b). Heterometric and heterogeneous, rounded, volcanic and sedimentary gravel and pebbles in sandy to silty matrix.
Recent alluvial deposit (b_a). Laminated sandy layers interbedded with volcanic, sedimentary and crystalline gravel deposits. These deposits fill depressions due to lava dam and form coast plain and alluvial fan at the end of deep valleys.

MOUNT ETNA VOLCANIC DISTRICT
MONGIBELLO VOLCANO
IL PIANO SYNTHEM

Torre del Filosofo formation (UTF)
Lava flows and fall pyroclastic deposits (bombs and lapilli) related to the summit crater and some lateral cones. Lava form flows mainly with aa and block morphology, rarely pahoehoe. Lava is basaltic to benmoreitic in composition, aphyric to high porphyritic in structure, phenocrysts of plagioclase, pyroxene, olivine changing in quantity and ratio. The age is from 15 ka to the present.
The lava flows of this unit are displayed with 5 time intervals.
Interval lava flows 1971 to present (i5): 1991-93, 1990, 1989, 1986-87, 1985, 1984, 1983, 1979, 1978, 1975-77, 1975, 1971.
Interval lava flows 1669 to 1971 (i4): 1968, 1956, 1950-51, 1928, 1908, 1892, 1886, 1883, 1869, 1865, 1852-53, 1842, 1819, 1811, 1802, 1792-93, 1766, 1763, 1689.
Interval lava flows 122 BC to 1669 (i3): 1634-38, 1537, 1444, 1408, Ballo (i3 ba), Petrulli (i3 pu), Fleri (i3 fe), Scorciavacca (i3 sr), M. Rinatu (i3 ri), M. Solfizio (i3 fs), 122 BC.
Interval lava flows 3.9 ka to 122 BC (i2): M. Arcimis (i2 am), Airone (i2 ai), Cancellieri (i2 ck), Pisano (i2 pi), Chiesa Vecchia (i2 cv), Mangano (i2 ma), Passopomo (pa), M. Salto del Cane (sd), S. Alfio e Cirino (ac), Casa Cangemi (i2 cg), Casa Pappalardo (i2 ap), M. Ilice (i2 mi), Serruggeri (i2 sg), Dagala (i2 da), Contrada Magazzeni (i2 co), M. Frumento delle Concazze (i2 fc), Valle della Scomunica (i2 so), Crisimo (i2 cr), M. Conconi (i2 mc). Sicani eruption (Sicani).
Interval lava flows 15 ka to 3.9 ka (i1): Case del Vescovo (i1 ve), Contrada Nocille (i1 no), Ripa Saldara (i1 rs), Vallone S. Giacomo (i1 vg), Montargano (i1 ag), Gona (i1 go), Casa Sambuco (i1 sb), Contrada Saette (i1 se), Villaggio Musco (i1 vm), Nucifora (i1 nu), Vallone Pozzillo (i1 vp), Pozzillo (i1 pz), Torrente Fago (i1 fg), M. Pomiciaro (i1 pm), Contrada Serracozzo (i1 cs), Andronica (i1 an), Dispensa Nuova (i1 dn), Monteleopoli (i1 me), M. Scuderi (i1 su).

i5
i4
i3
c i2
a
b
i1

Chiancone member (a) (UTF_{03}): Volcaniclastic deposit, poorly stratified, lithologically heterogeneous, made by centimetric to metric rounded pebbles and gravel with poor sandy to silty matrix. At the base a maximum 4 m succession constituted by at least 4 welded debris flow layers matrix supported crops out. The maximum cropping out thickness is 30 m; the overall thickness is indeterminable, however higher than 200 m.
Milo member (b) (UTF_{02}): At the base monogenetic debris avalanche deposit, constituted by mugearitic lava pebbles up to 1 m, sometimes with jigsaw cracks, in abundant loose matrix made by the same altered lava. At the top succession of debris flow deposits, mainly matrix supported. The thickness is from few meters to 30 m.
Cubania member (c) (UTF_{01}): Succession of pyroclastic fall layers interbedded with yellow silty to sandy aeolian deposits and with brown paleosols, darker and carbonaceous at the top. Tephra composition is picritic to mugearitic. Clasts are scoriaceous and mainly porphyritic, with plagioclase,

CONCAZZE SYNTHEM
ELLITTICO VOLCANO

Portella Giumenta formation (GUM)
Pyroclastic succession associated with lava flows divided into two members (age about 15 ka).
Osservatorio Etneo member (a) (GUM_{01}): Pyroclastic proximal fall deposit constituted by black scoriaceuos spatters that become reddish and partially welded at the top. Locally the spatters form massive red and gray beds with inner aphyric black portions. At the bottom of this level, a yellowish pumice bed outcrops. The distal deposits are formed by four light gray pumice lapilli layers interbedded with paleosols deposits. Trachitic-benmoreitic in composition. Pumice clasts are oligophyric with phenocrysts of plagioclase, pyroxene, amphibole and olivine. Maximum thickness 10 m.
Ragabo member (b) (GUM_{02}): Reomorphic lava flows light gray to reddish brown in color, often banded. Benmoreite in composition. Subaphyric structure with rare phenocrysts of plagioclase, pyroxene and amphibole. Maximum thickness 10 m.

a b

Field work: STEFANO BRANCA, SONIA CALVARI, MAURO COLTELLI, VICTOR HUGO GARDUNO, GIANLUCA GROPPELLI, LUIGI LODATO, MARCO NERI, GIORGIO PASQUARE
GIS and geological data base input: FRANCESCA ARDIZZONE, SIMONE STERLACCHINI

Piano Provenzana formation (UPP)
Lava flows and scoria cones remnants. Lava is hawaiitic to benmoreitic in composition, aphyric to porphyritic in structure, with phenocrysts of plagioclase, pyroxene, olivine.
Lava flows: Vignagrande (UPP vi), Malasorba (UPP mb).
Tripodo member (a) (UPP_{03}): Hawaiitic lava flows with, at the base, porphyritic structure and abundant phenocrysts of plagioclase and pyroxene, at the top subaphyric structure and flow foliation. Discontinuous interbedded ash layers. The member is 10 to 50 m thick and outcrops only in the Piano della Lepre.

a b c

Zoccolaro member (b) (UPP_{02}): Lava flow succession, mugearite in composition, porphyritic in structure with phenocrysts of plagioclase, pyroxene and abundant olivine. The thickness is from few meters to more 100 m.
Tagliaborse member (c) (UPP_{01}): Pyroclastic fall layers made of ashes and scoriaceous lapilli interbedded with yellow aeolian silt deposits and to black sand beds. Tephra composition is basaltic to hawaiitic. Clasts are scoriaceous and often porphyritic with phenocrysts of pyroxene, olivine, amphibole, changing in quantity and ratio. The maximum thickness is 10 m. The age is more than 16 ka.

Pizzi Deneri formation (FPD)
Thick lava flows interbedded with volcanoclastic deposits (autoclastic and epiclastic breccia) with yellow fine welded matrix. Lava is hawaiitic to mugearitic in composition, porphyritic in structure, with phenocrysts of plagioclase, pyroxene, olivine. The plagioclase size regularly increases to the top, where it reaches 1 cm. The thickness is few meters to more than 150 m.

Serra delle Concazze Formation (SDZ)
Flow and fall pyroclastic deposits interbedded with blast breccia and epiclastic deposits. Four thick lava flows (more than 100 m thick) are interlayered into the volcanoclastic deposits. Lava is hawaiitic to benmoreitic in composition, subaphyric to high porphyritic in structure, with phenocrysts of plagioclase, pyroxene, olivine. Along the western wall of the Valle del Bove thin lava flow succession interbedded with pyroclastic and epiclastic deposits outcrops. The thickness is 100 to 400 m.

Monte Scorsone Formation (SRS)
Pyroclastic layers and lava flows. A pumiceous hydromagmatic deposit, light grey in colour, at the base, is covered by a succession of scoriaceous lapilli layers, blast and epiclastic breccia and thin ashy layers (about 10 m thick). Near the top they gradually change to lava flows frequently interbedded with pyroclastic and epiclastic layers (about 200 m thick). Lava composition is often mugearite with phenocrysts of plagioclase, pyroxene, olivine and rare amphibole changing in quantity and ratio. The thickness is up to 250 m.

Contrada Ragaglia formation (UCG)
Debris flow deposit made of eterogeneous lava blocks up to some meters in size in a clay matrix. Locally at the top the deposit changes to silty-sandy epiclastic layers, brown in colour interbedded with some bad preserved pyroclastic pumiceous and scoriaceous layers. The thickness is up to 40 m.

GIROLAMO SYNTHEM
CUVIGGHIUNI VOLCANO

Volta del Girolamo formation (FVG)
Lava flows mugearitic in composition, porphyritic in structure with phenocrysts of plagioclase, pyroxene, olivine. The thickness is about 100 m.
Canalone della Montagnola Formation (CGA)
Thin lava flows overlapped by a thick pyroclastic and epiclastic succession, variable in colour, thickness and dip. Lava is mugearitic in composition, porphyritic in structure with phenocrysts of plagioclase, pyroxene, olivine and amphibole. The thickness is from few meters to 300 m.

Serra Cuvigghiuni formation (USC)
This formation is constituted by some necks (USC_{01}) associated to thin lava flows (USC) at the top.
neck member (a) (USC_{01}): subvolcanic bodies made of pink massive lava, with columnar joints, mugearitic to benmoreite in composition, high porphyritic in structure with phenocrysts of plagioclase, pyroxene, and amphibole.
At the top, thin lava flows (b) (USC) of the same composition coming from the neck. The thickness is 20 m.

b a

ZAPPINI SYNTHEM
SALIFIZIO VOLCANO

Acqua della Rocca formation (UAR)
Lava flows interbedded with epiclastic deposits. Lava is benmoreite in composition, porphyritic in structure with phenocrysts of plagioclase, pyroxene and rare olivine. At the top a welded scoria layer outcrops; scoria structure is subaphyric with rare phenocrysts of plagioclase and amphibole. The thickness is 100 m.

Serra del Salifizio Formation (SDF)
Leucocratic lava flows interbedded with thin epiclastic deposits. Lava is mugearitic to benmoreitic in composition, porphyritic in structure with phenocrysts of plagioclase, pyroxene and amphibole. Each lava flow is 2 to 10 m thick. The Formation thickness is 150 m.

Serra del Salifizio Formation (SDF)
Leucocratic lava flows interbedded with thin epiclastic deposits. Lava is mugearitic to benmoreitic in composition, porphyritic in structure with phenocrysts of plagioclase, pyroxene and amphibole. Each lava flow is 2 to 10 m thick. The Formation thickness is 150 m.

GIANNICOLA VOLCANO

Serra Giannicola Grande Formation (SGN)
This formation is constituted by some necks (SGN_{01}) associated to lava flows and autoclastic breccia (SGN) at the top.
Neck and associated lava flows and autoclastic breccia.
neck member (a) (SGN_{01}): subvolcanic bodies made of pink massive lava, with columnar joints, mugearitic in composition, high porphyritic in structure with oriented phenocrysts of plagioclase, pyroxene, amphibole and rare olivine. The thickness is > 300 m.
Lava flow succession interbbeded to light brown pyroclastic deposits and autoclastic breccia (SGN). Lava is hawaiitic to mugearitic in composition, porphyritic in structure with phenocrysts of plagioclase, pyroxene and olivine. The thickness of the lava flow succession is 200 m.

b a

ACIREALE SYNTHEM
TRIFOGLIETTO VOLCANO

Piano del Trifoglietto formation (UPT)
Autoclastic breccia and epiclastic deposits interbedded at the base with rare pyroclastic flow deposits; at the top thin and discontinuous lava flows interlayered to pyroclastic deposits with yellow and light brown matrix. Lava is benmoreitic in composition, porphyritic in structure with phenocrysts of plagioclase, pyroxene and olivine. The thickness is over 300 m.

ROCCHE VOLCANO

Delle Rocche formation (UDR)
This formation is constituted by a complex succession: thin lava flows, autoclastic lavas and volcaniclastic deposits.
Rocca Capra member (a) (UDR_{01}): Lava flows interbedded with autoclastic breccia and epiclastic deposits, matrix supported, yellow in colour. Lava is hawaiitic to mugearitic in composition, porphyritic in structure with phenocrysts of plagioclase, pyroxene and olivine. The cropping out thickness is about 100 m.
Rocca Palombe member (b) (UDR_{02}): Lava flows interbedded with a red pyroclastic flow deposit, 30 m thick. Lava is mugearitic in composition, porphyritic in structure with phenocrysts of plagioclase, pyroxene, olivine and amphibole. Scoria structure is aphyric. The cropping out thickness is about 60 m.

a b

TARDERIA VOLCANO

Contrada Passo Cannelli formation (UCP)
Massive lava flows locally interbedded with epiclastic deposits with sandy matrix and heterometric blocks made of the same lava. Lava is hawaiitic to benmoreitic in composition, porphyritic in structure with phenocrysts of plagioclase, pyroxene, and olivine. Lava flows at the top are lacking in scoria and present aeolian erosion. The cropping out thickness is over 30 m.

Calanna formation (UCN)
Cataclastic lavas with yellow clay matrix associated to numerous altered dikes (UCN). Lava is basaltic to mugearitic in composition, porphyritic in structure with large phenocrysts of pyroxene and plagioclase. The cropping out thickness is about 200 m.
M. Calanna member (a) (UCN_{01}): Thin lava flows interbedded with scoria deposits. Lava is hawaiitic in composition, porphyritic in structure with phenocrysts of plagioclase and pyroxene. The thickness is about 30 m.

a

Moscarello formation (UML)
Massive and thick lava flows with rare interbedded pyroclastic deposits. Pyroclastic deposits are constituted by red scoriaceous bombs. Lava is usually mugearitic in composition, subaphyric to porphyritic in structure with phenocrysts of plagioclase and pyroxene. The maximun thickness is 150 m.

TIMPE SYNTHEM

La Timpa formation (UTM)
This formation is constituted by lava (lava flows and subvolcanic bodies) with composition changing from basalt to Na-mugearite.
Fondo Macchia member (UTM_{01}): Thick massive lava flows. Lava structure is porphyritic with large phenocrysts of pyroxene, olivine and plagioclase. The maximun thickness is about 70 m.

Timpa di Don Masi formation (TDM)
Basalts, tholeiitic in affinity, porphyritic in structure with phenocrysts of plagioclase, pyroxene and olivine.
Fermata S. Venera member (TDM_{02}): Altered lava flows dislocated in metric blocks at the boundary with the sedimentary rocks. The maximun thickness is 30 m.

QUATERNARY MARINE DEPOSITS

Argille grigio-azzurre Formation (FAG)
Blue-grey marly clays ($CaCO_3$=10-15%), in partial etheropic passage with the underlying calcarenites. Foraminiferal content characterized by the presence of *Hyalinea baltica, Globorotalia inflata* and *Globorotalia truncatulinoides excelsa*. The basal horizons yield nannofossil assemblages of the MNN19e biozone; nannofossil of the subsequent MNN19f biozone within the intermediate and upper levels (FAG). At Fermata S. Venera the clays are unconformably covered by discontinuous alluvial conglomerates made up of heterogeneous sedimentary clasts. Maximum thickness of about 80 m at Serra S. Biagio hill. Age: Early (Sicilian)-Middle Pleistocene.

Fig. 2 - *View of the inner wall of the Valle del Bove. The wall is very steep and 800-to-300 m high and enables the observation of the oldest scattered volcanic centres. For their location see also Fig. 17.*

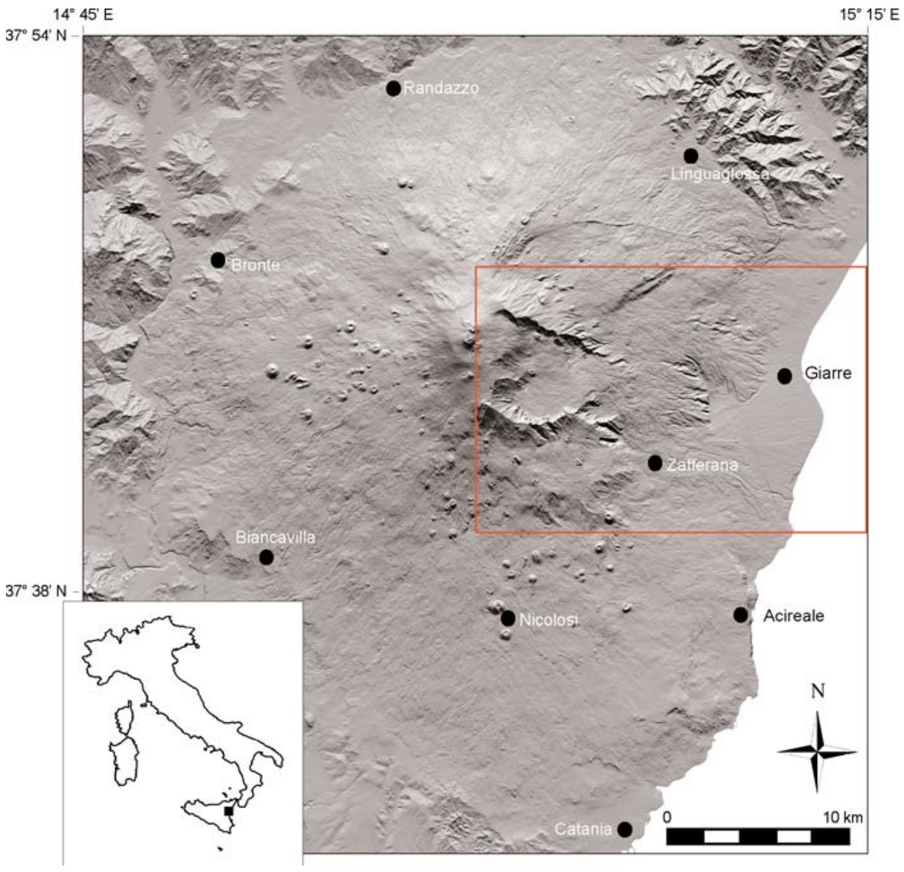


Fig. 3 - *Shaded image of Mt. Etna's digital elevation model. The artificial lighting is from the north and has an elevation of 45°. The box shows the area of the geological map of Fig. 1 (modified from* PARESCHI et alii, *1999).*

INTRODUCTION

The data presented here are based on new stratigraphic studies and geological mapping carried out on the eastern flank of Etna, from the summit craters to the coast, as part of the work for the new 1.50,000 scale geological map of Italy (625 - Acireale Sheet). The whole area is characterised by the superposition of effusive, explosive and reworked volcanic products, that together represent the lithological and morphological history of the main portion of the volcano. The geological map presented here (Fig. 1 and 3) is a significant portion of the Acireale Sheet, in which it is possible to observe the best and most complete volcanic succession of the Mt. Etna Volcano. The geological field survey was carried out at a 1:5,000 to 1:10,000 scale, depending on geological complexity and exposure.

The present example appears to be especially suited for the purposes of establishing the appropriate stratigraphic methodology to be used in mapping a recent composite volcano. The first attempts at applying this methodology were presented in the official guidelines of the National Geological Survey of Italy published in 1992 by PASQUARÈ *et alii*. The example presented here refers to the study of the very steep and well-exposed Valle del Bove walls (Fig. 2), which had also already been published by CALVARI *et alii* (1994) and COLTELLI *et alii* (1994).

GEOLOGICAL SETTING

Eastern Sicily is characterised by three different structural domains (Fig. 4) emplaced during the Neogene, the last stage of the Europa-Africa plate collision:

1) the orogenic domain belonging to the Apennine-Maghrebian Belt;

2) the Gela Foredeep filled by Pliocene-Quaternary sediments;

3) the foreland domain, known here as the Hyblean Plateau, representing part of the undeformed African continental margin.

The long tectonic history of this region was associated to episodic volcanic activities from the Late Trias up to the present. The oldest volcanism was located inside the Hyblean plateau, and lasted up to the Middle Pleistocene (CARBONE *et alii*, 1982). From the Late Miocene, the Hyblean volcanism gradually extended northward up to the Etna area, where pillow-lava effusions, dated back to about 600 ka (GILLOT *et alii*, 1994), are considered to be the first testimonies of the Etna volcanic activity.

Mt. Etna is the largest and most active European volcano, covering an area of 1250 km^2 and reaching an elevation of 3340 m. The Mt. Etna volcanics rest on the Gela foredeep sediments to the south and southeast and on the Apenninic-Maghrebian sedimentary units to the north and northwest (DI STEFANO & BRANCA, 2002). The lower eastern flank of Etna is dissected by the active NNW-SSE-trending Timpe fault system (LO GIUDICE *et alii*, 1982; AZZARO, 1999), the northern inland termination of the Malta Escarpment, a major lithospheric fault system extending for about 300 km southwards from Etna volcano (SCANDONE *et alii*, 1981; BEN AVRAHAM & GRASSO, 1991; TORELLI *et alii*, 1998). Recently, DOGLIONI *et alii* (2001) have proposed the origin of Etna's magmatism to be the result of subduction rollback with right-lateral transtension that might produce a vertical slab window (Fig. 5).

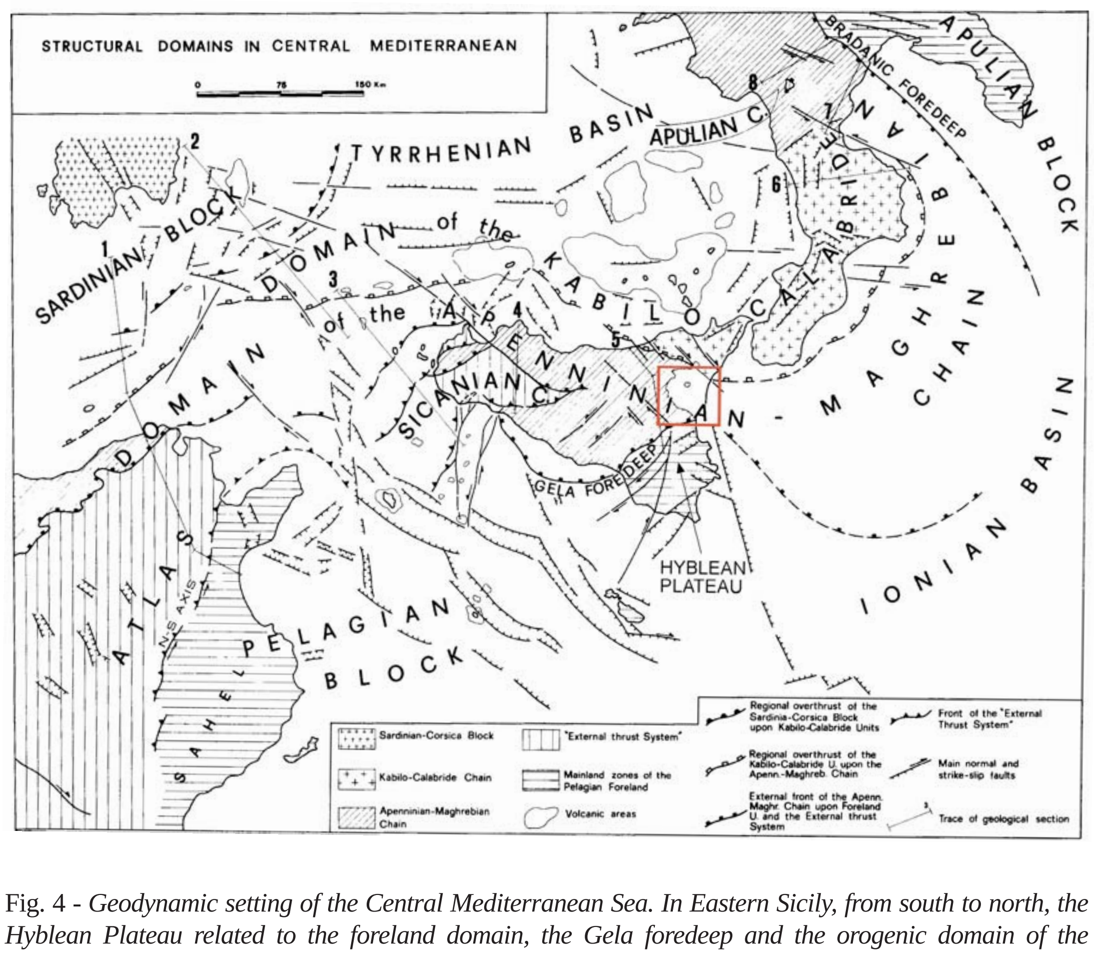


Fig. 4 - *Geodynamic setting of the Central Mediterranean Sea. In Eastern Sicily, from south to north, the Hyblean Plateau related to the foreland domain, the Gela foredeep and the orogenic domain of the Apenninian-Maghrebian and Kabilo-Calabride belts can be distinguished (from* LENTINI et alii, *1994, modified). The red box shows the area of Fig. 3.*

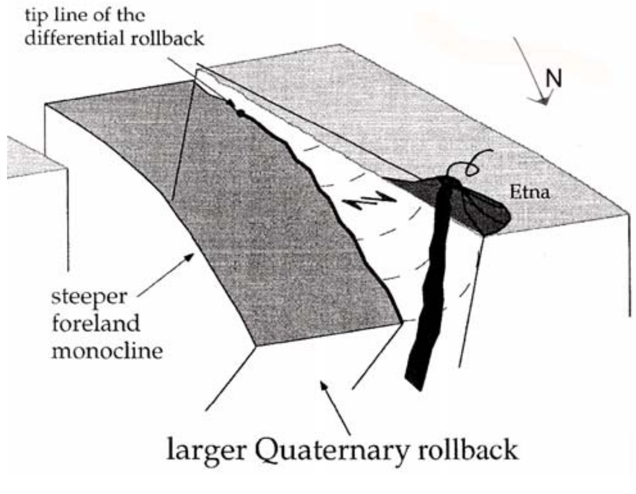


Fig. 5 - *Hypothetical emplacement of the Mt. Etna volcano along the Malta-Hyblean active, right-lateral transtensional fault zone. The differential subduction rollback along this fault system may produce a vertical slab window, which in turn might comprise Etna's magmatic source (modified from* DOGLIONI et alii, *2001).*

STRATIGRAPHIC METHODOLOGY

Lithostratigraphy was the main stratigraphic criterion used in the identification of volcanic units during the field surveys of Mt. Etna's eastern flank. Different ranks of lithostratigraphic units (from lava flow to formation, Fig. 8) were adopted as the main stratigraphic tool during the fieldwork and its cartographic representation (see Fig. 1 and the relative legend). Furthermore, the Unconformity Bounded Stratigraphic Units (UBSU) (SALVADOR, 1987) were also adopted, in accordance with the guidelines suggested by ISSC for the UBSU (SALVADOR, 1994) and by the National Geological Survey of Italy (PASQUAR *et alii*, 1992). The UBSU were preliminarily applied in the Valle del Bove area (PASQUAR *et alii*, 1992; CALVARI *et alii*, 1994; COLTELLI *et alii*, 1994), where the main unconformities within the volcanic succession are well exposed in the inner walls of the depression.

The recognition of unconformity surfaces within the volcanic succession has enabled several lithostratigraphic units to be grouped in synthemic units. The main unconformities recognized in the Valle del Bove area are represented by angular unconformities associated to erosion surfaces (Figs. 10 and 11) that mark periods of quiescence occurring between successive stages of volcanic activity. On the whole, this type of unconformities indicates a shifting of the magmatic feeding system with overlapping of related volcanic centres.

We defined the different rank of the unconformities through the evaluation of:

a) their geographic extension;

b) their temporal hiatus;

c) the entity of their geological, geomorphologic and structural changes.

In addition to these two categories of stratigraphic units, lithosomatic units were also adopted in order to better represent the spatial localization of the different eruptive centres, recognised on the basis of their morphology (Fig. 13). Thus the lithosomes enable the recognition of the position of the successive volcanic centres in the relative time record.

The stratigraphic framework proposed for the eastern flank of Etna volcano is, therefore, the result of a combination of the

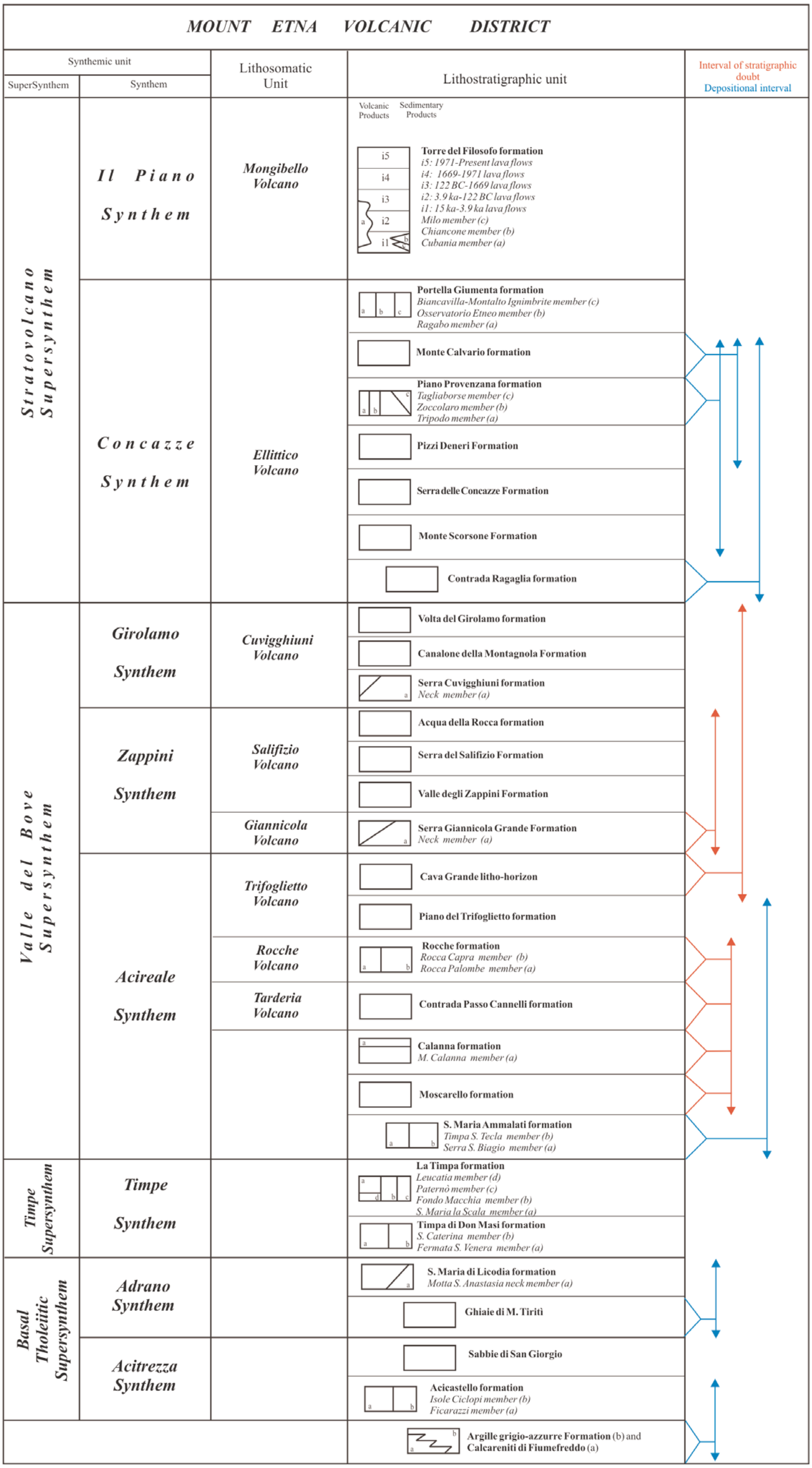


Fig. 6 - *Sketch of the stratigraphic units relationship of the entire Mt. Etna 1:50,000 scale geological map. Each stratigraphic category may be considered as being autonomous and investigated separately from the others. The first column shows the synthemic units, the second lithosomatic units, and the third lithostratigraphic units of different rank. In the last column, two arrows of different colour show the deposition interval of certain units (in* blue) *when they are eteropically correlated, and the interval of stratigraphic doubt* (in red) *due to the lack of clear stratigraphic relationships (from* BRANCA et alii*, 2004).*

Fig. 7 - *The 2002 eruption forming the scoria cone along the southern flank of Mt. Etna Volcano. Picture taken in November 2002.*

above-described stratigraphic units, as indicated in Fig. 6. The aim of this stratigraphic framework is to clearly evidence the complex setting of the spatial and temporal evolution of the volcanic system and the surrounding environment. The relationships between the different categories of stratigraphic units are shown in Fig. 6, where the temporal extension of certain long-living and eteropic units is represented with blue arrows, while temporal and stratigraphic uncertainty is indicated by red arrows.

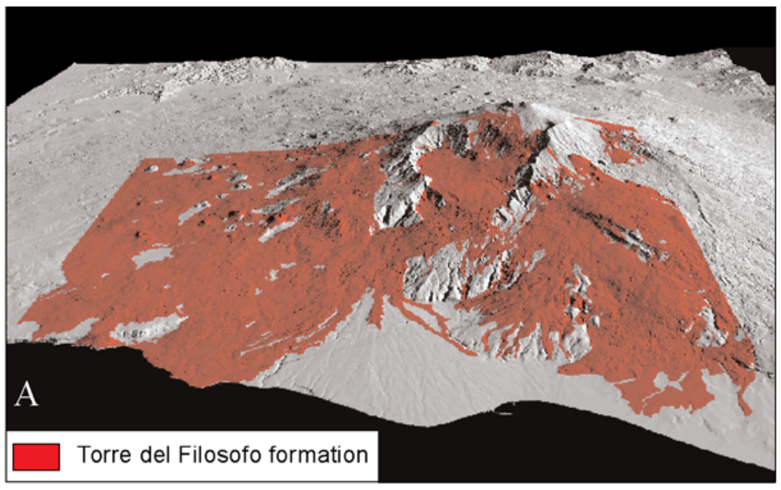
LITHOSTRATIGRAPHIC UNITS

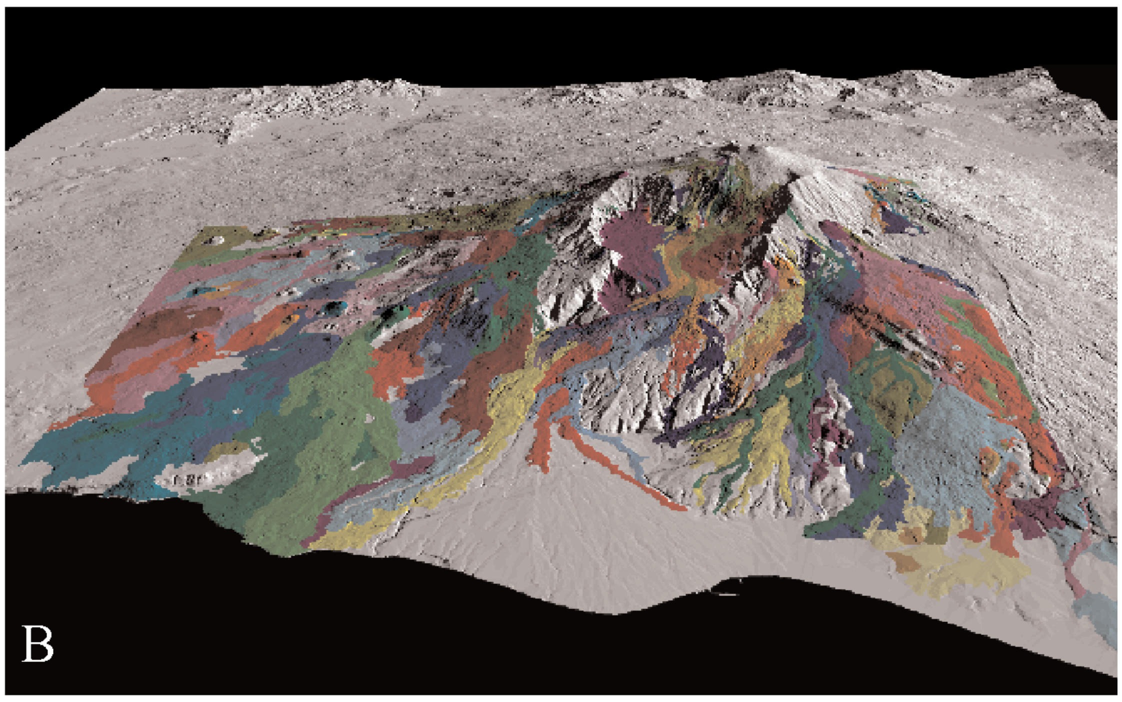
In accordance with International Guidelines (SALVADOR, 1994), lithostratigraphy has been used as the main stratigraphic rule for the identification of the units during the surveys of Mt. Etna Volcano. The Etna volcanic succession was divided into lithostratigraphic units of different ranks from formations to members (when important lithological differences were recognised) or lava flow for the youngest products (last 15 ka) (Fig. 1).

The use of lithostratigraphic units is very important during the first survey phase, because only the lithological properties and stratigraphic relationships are immediately recognisable during fieldwork, while laboratory data, derived from petrographic, geochemical and radiometric analyses, allow a better subsequent definition of the identified units.

Fieldwork was carried out at scales ranging from 1:5,000 to 1:10,000, depending on geological complexity and different exposure, with outcrops often located along deep scarps. Numerous detailed stratigraphic sections were logged along the steep wall of the Valle del Bove depression, where the products related to the oldest volcanoes outcrop, and well-exposed vertical sections could be recognised.

A particular problem arose in the cartographic visualization of the products erupted by the Mongibello volcano. The volcanics erupted during this last stage of Mt. Etna activity cover 85% of the area presented in this work. Most of these are lava flows, which, due to their limited lithological variability and their nearly continuous temporal succession, have been grouped into a single lithostratigraphic unit called the Torre del Filosofo formation (Fig. 8A). During the geological survey of the area, each lava flow was represented separately on the topographic field map. Otherwise, in drafting the geological map, a single colour would have had to be used for all the lava flows of the Mongibello Volcano - as these stratigraphically belong to a single formational unit composed of more than 130 different lava flows. This solution would have prevented the cartographic visualisation of the time-space behaviour of the effusive activity over the last 15,000 years (see Fig. 8A), including the many historical and sub-actual manifestations that comprise a fundamental goal of the map itself.





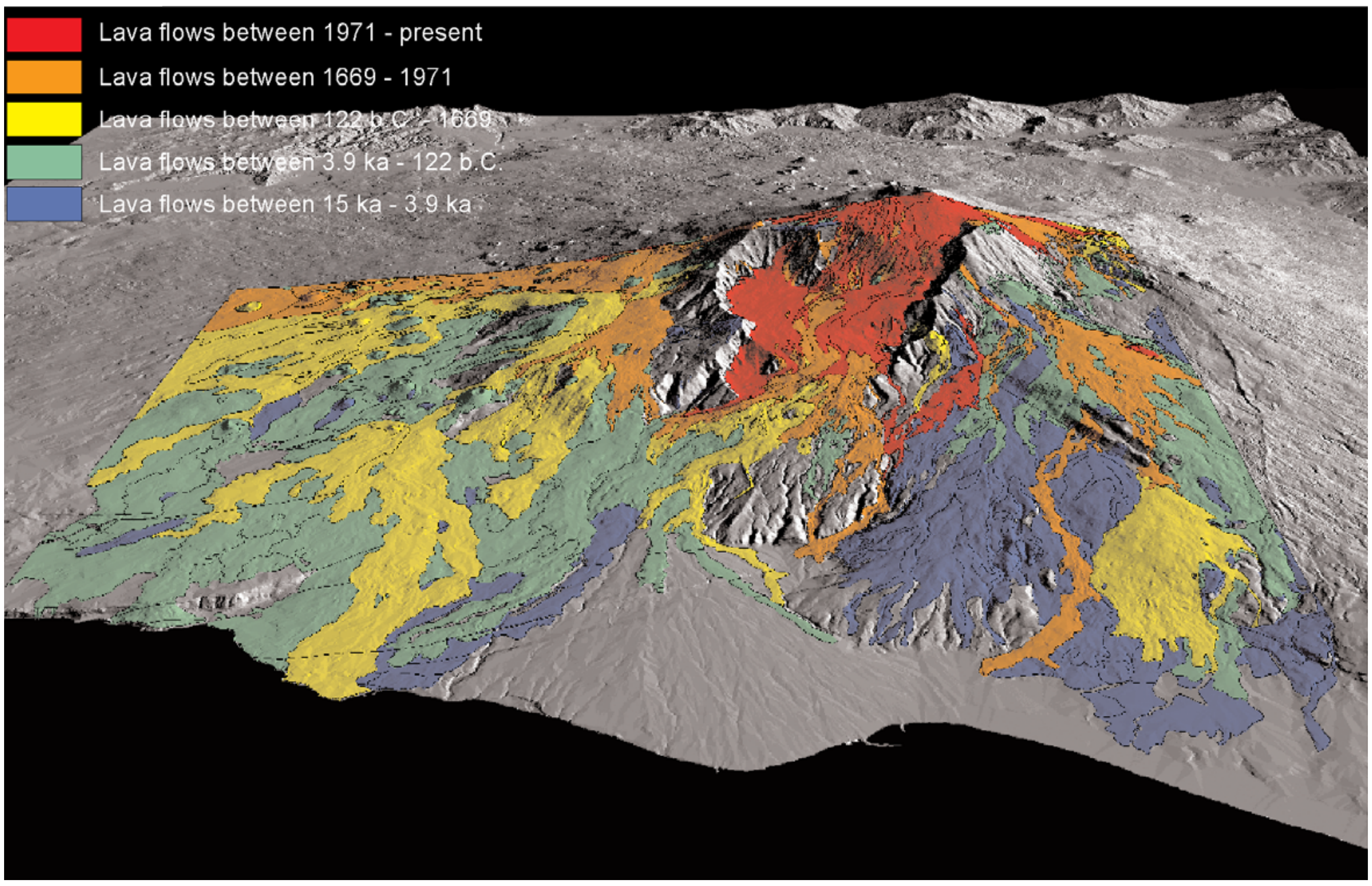


Fig. 8 - *3D different representations of the lava flows belonging to the Torre del Filosofo formation. These lava flows cover more than 85% of the Acireale Sheet:* A) *no individual lava flow is distinguished within the Torre del Filosofo formation;* B) *each individual lava flow is shown in a different colour; and* C) *the lava flows belonging to the Torre del Filosofo formation are grouped in five time intervals.*

The proposed solution groups together the mapped lava flows belonging to the Torre del Filosofo formation into five time intervals depicted in five different colours (Figs. 8c and 1), with the boundaries between lava flows defined by means of a univocal label. The time intervals are limited by significant eruptions in the evolution of the Mongibello Volcano. The products related to these eruptions cannot represent the marker boundaries of members of the same formation, because of the lithological similarity between the lava flows of the different intervals and the lack of key-markers of reliable lithostratigraphic importance. Although the use of such intervals does not comply with standard stratigraphic procedures, they nevertheless should be considered, in this particular framework, as a practical tool for illustrating a very important geological and volcanological data-set.

The first time interval spans from the top of the plinian benmoretic-trachitic deposits related to the Ellittico caldera collapse and the sub-plinian picritic eruption that occurred in the Mongibello volcano about 3.9 ka ago, marking a remarkable increase in the eruptive rate of the volcano.

The second interval spans from the above-mentioned sub-plinian picritic eruption to the plinian eruption of 122 BC, the strongest explosive eruption of the Mongibello volcano.

The third interval spans from the plinian eruption of 122 BC to the eruption that occurred in 1669 AD, the most voluminous effusive eruption of Mt. Etna Volcano recorded during historical times.

The fourth interval covers the period from the 1669 AD eruption to the 1971 AD lava flow.

The fifth interval goes from the 1971 AD eruption to the Present and corresponds to the last intense eruptive activity of the Mongibello volcano.

SYNTHEMIC UNITS

Unconformity Bounded Stratigraphic Units (UBSU) were proposed by Chang in 1975, and their use was recommended by SALVADOR (1987; 1994). PASQUARÈ *et alii* (1992) strongly supported their usefulness as a tool towards a clear stratigraphic interpretation of recent volcanic areas, and their proposal was followed by several geological surveys of Italian volcanoes (CALVARI *et alii* 1994; COLTELLI *et alii*, 1994; MANETTI *et alii*, 1995a; 1995b; ROSSI *et alii*, 1996; BELLUCCI *et alii*, 1999; CALANCHI *et alii*, 1999; DE RITA *et alii*, 2000; TRANNE *et alii*, 2002a; 2002b).

Several unconformities, different in rank and resulting from different causes, can be found in volcanic successions: a short or long period of quiescence, an erosional phase, a shift in the feeding system, an abrupt change in eruptive

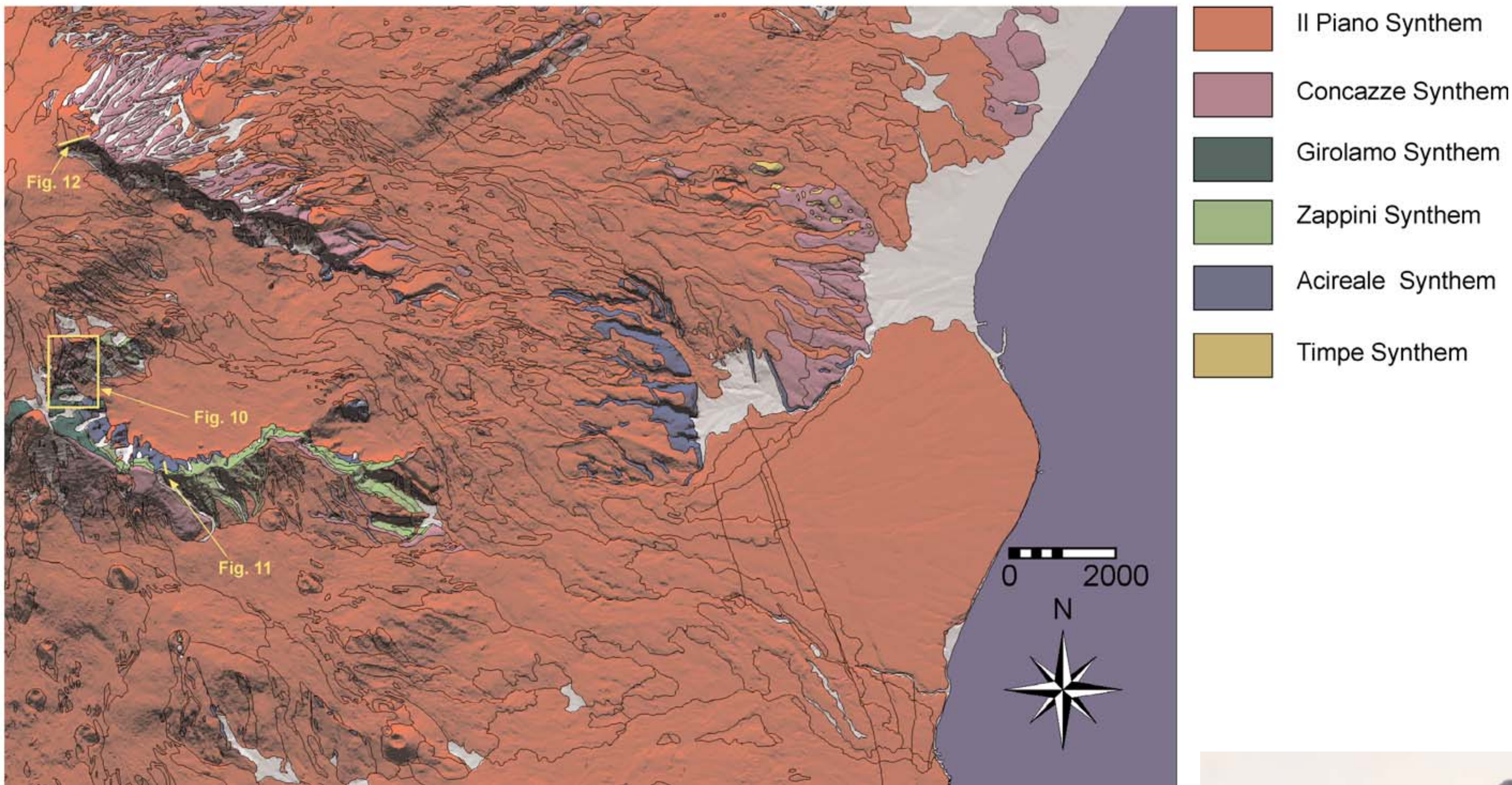


Fig. 9 - *Map of the eastern flank of Mount Etna based on synthemic units. The area is the same as that of Fig. 1. The map is a synthesis of the most important steps in the evolution of Mount Etna (see also Fig. 6). The grey areas are related to the recent fluvial deposit or to the talus. The yellow rectangle and lines show the location of the next Figs. Representation on a shadow digital elevation model.*

Fig. 10 - *View of the western wall of the Valle del Bove depression near Cisternazza. The thick and sub-horizontal lava flows (Concazze Synthem) overlap with pronounced angular unconformity the pyroclastic and epiclastic deposits of Girolamo Synthem. This angular unconformity is due to a shifting of the magmatic feeding system 4 km to north-west (see also Fig. 17, from Cuvigghiuni to Ellittico Volcanoes). See Fig. 9 for location.*

Fig. 11 - *View of the southern wall of the Valle del Bove depression near Vallone del Tripodo. The upper lava flows succession (Zappini Synthem) overlaps the epiclastic and piroclastic deposits of Acireale Synthem with moderate angular unconformity. This angular unconformity is due to a hiatus in the volcanic succession with a local shifting of the magmatic feeding system (see also Fig. 17, from Trifoglietto to Salifizio Volcanoes). See Fig. 9 for location.*

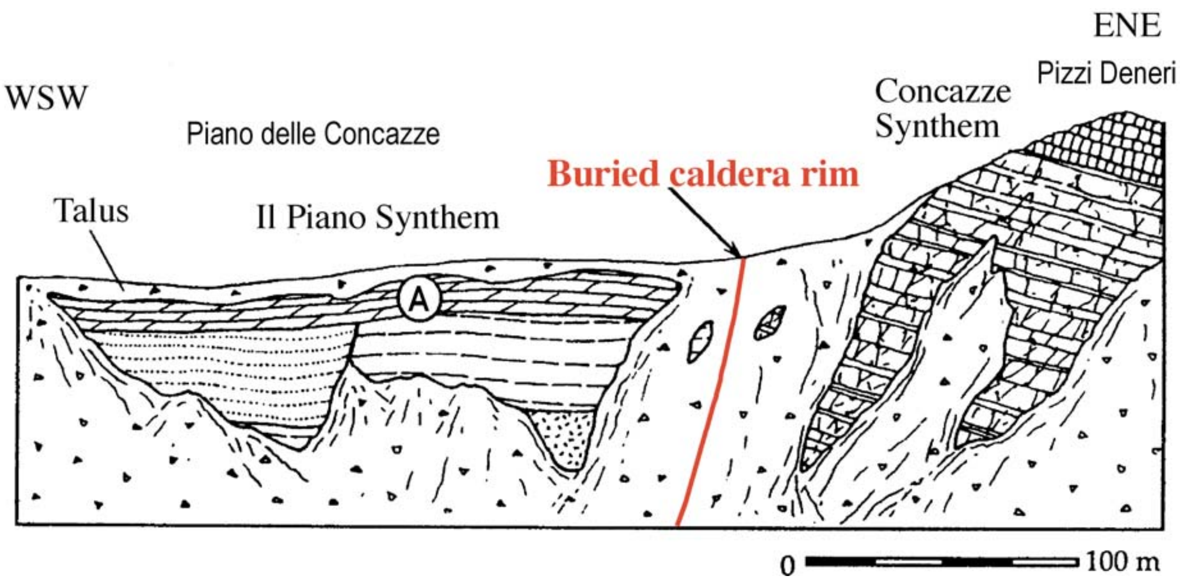


Fig. 12 - *Schematic view of the Valle del Leone and Piano delle Concazze area. The sub-horizontal lava flows (Il Piano Synthem) fill the caldera collapse depression and onlap the dip lava flows belonging to the Concazze Synthem. The caldera collapse occurred at the end of the Ellittico Volcano (see also "Geo-volcanogical evolution") (modified from* COLTELLI et alii, *1994). See Fig. 9 for location.*

style, a volcano-tectonic event, and a caldera or a flank collapse. The identification of unconformity surfaces within the volcanic succession enables the grouping of several lithostratigraphic units in synthemic units, each representing a well-defined step in the volcanic and geological evolution of the area. For this reason, it is advisable to identify the most important unconformities according to their geographic extension, the duration of their hiatus and their volcanic and geological significance. To this end, it is necessary to rule out all unconformity surfaces due to the usual emplacement of volcanic products during a well-defined volcanic cycle, and lacking in significant temporal hiatus (e.g. the surface between two lava flows erupted from the same vent or the local and discontinuous unconformities within a lava flow field). Unconformities in the proximal areas of volcanoes, such as the Valle del Bove depression, are commonly represented by erosion surfaces associated to angular discordances (Figs. 10 and 11), generated both during periods of quiescence and shifting in the volcano feeding system and during important changes in the morphology and structure of the emission centres. Conversely, in distal areas, unconformities are represented by erosion surfaces due to morphological and fluvial re-organisation as a consequence of eruptive centres shifting, or due to important tectonic deformations in the area hosting and surrounding the volcano (BRANCA & CATALANO, 2000). In the latter case, unconformities may also consist in depositional disturbances in any continental or shallow marine basins located around the volcano.

Taking into account the first definitions of UBSU (CHANG, 1975; SALVADOR, 1987; 1994), their application in volcanic areas presents some problems of scale (temporal and spatial), because usually the hiatus separating the different units has a short duration in terms of geological times, and a limited areal extent when related only to the eruptive, structural or morphogenetic evolution of one or more volcanic centres.

A map based on synthemic units (Fig. 9) can represent the main steps in the evolution of Mt. Etna Volcano, as identified through objective characteristics, such as unconformity boundaries (for further details on the evolution of Mt. Etna, see the paragraph "Geo-volcanological evolution"). The more frequent unconformity boundaries on Mt. Etna Volcano are related to angular unconformities caused by a shift in the volcanic feeding system (Fig. 10), sometimes with a prolonged period of quiescence associated to a production of epiclastic deposits (Fig. 11). In the case of the Concazze Synthem, the upper boundary is related to an important volcano-tectonic event, i.e. the Ellittico caldera collapse (Fig. 12).

LITHOSOMATIC UNITS

Following the recommendations of PASQUARÈ *et alii* (1992), we utilised lithosomes as informal stratigraphic units in order to complete the local stratigraphic column and to map volcanic centres that are still morphologically recognisable. In their original definition (WHEELER & MALLORY, 1953), lithosomes are adimensional and out of hierarchy. In the case of a complex composite volcano such as Mt. Etna, we propose to use lithosomes to introduce through them, in the stratigraphic record, certain fundamental morpho-volcanological distinctions, such as, for example, that between great stratocones and small monogenetic cones. In our work, lithosomes belonging to the first of the two categories mentioned are indicated by the term "volcano" followed by a geographical name (Fig. 13). This solution enables even non-geologists to understand volcanic evolution through an easier reading of the geological map.

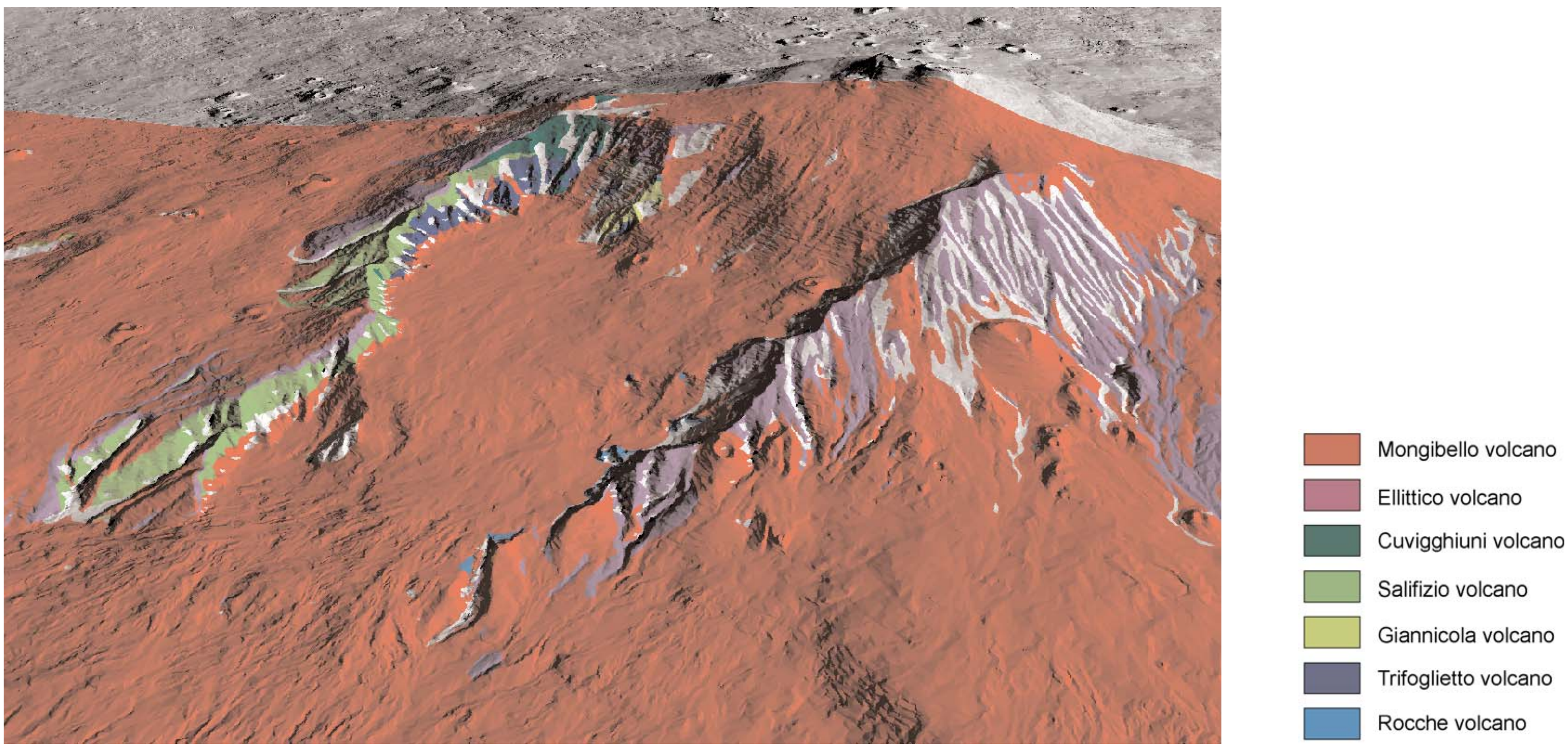


Fig. 13 - *3D view of the Valle del Bove depression and summit craters from the north-east. It is possible to observe the morphological remnants of the northern and southern flanks of the Ellittico Volcano and their relations with the previous smaller volcanic centres. The southern inner scarp of the Valle del Bove depression appears to be particularly suited to this purpose. The gray areas are related to the fal. See Fig. 17 for volcano distribution.*

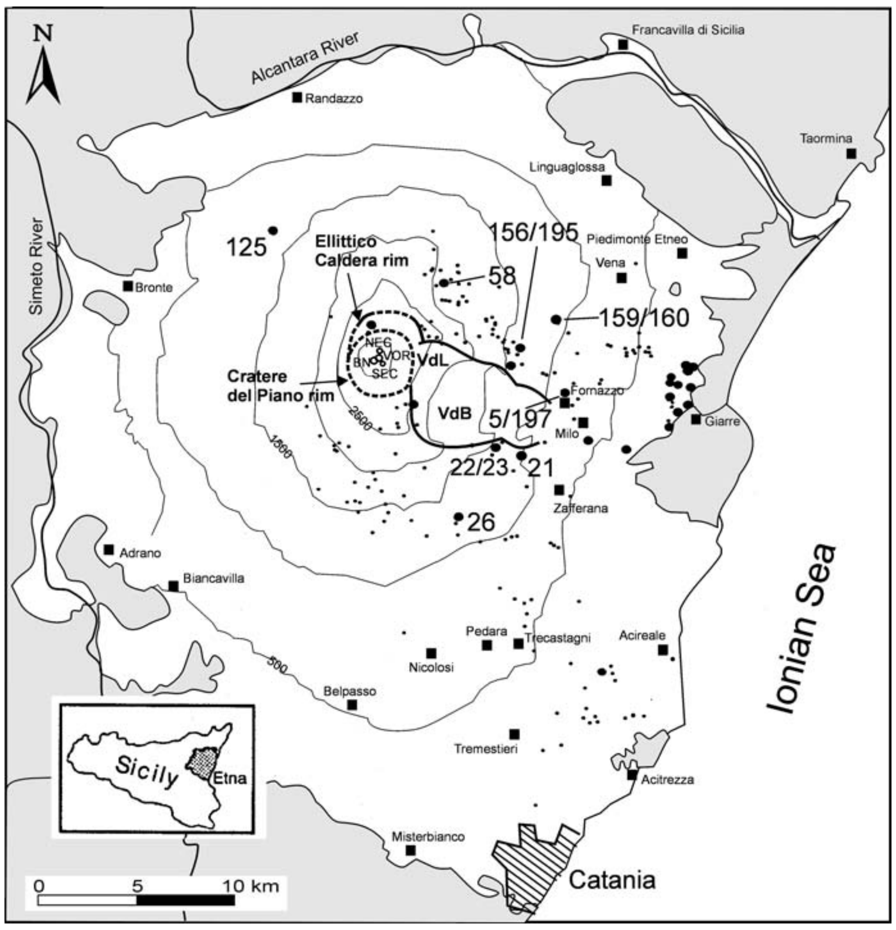


Fig. 14 - *Points indicate the location of the studied stratigraphic sections; numbers are stratigraphic sections shown in Fig. 15; squares are villages or towns.* BN=*Bocca Nuova;* VOR=*Voragine;* NEC=*North East Crater;* SEC=*South East Crater;* VdB=*Valle del Bove;* VdL=*Valle del Leone (from* DEL CARLO et alii, *2004).*

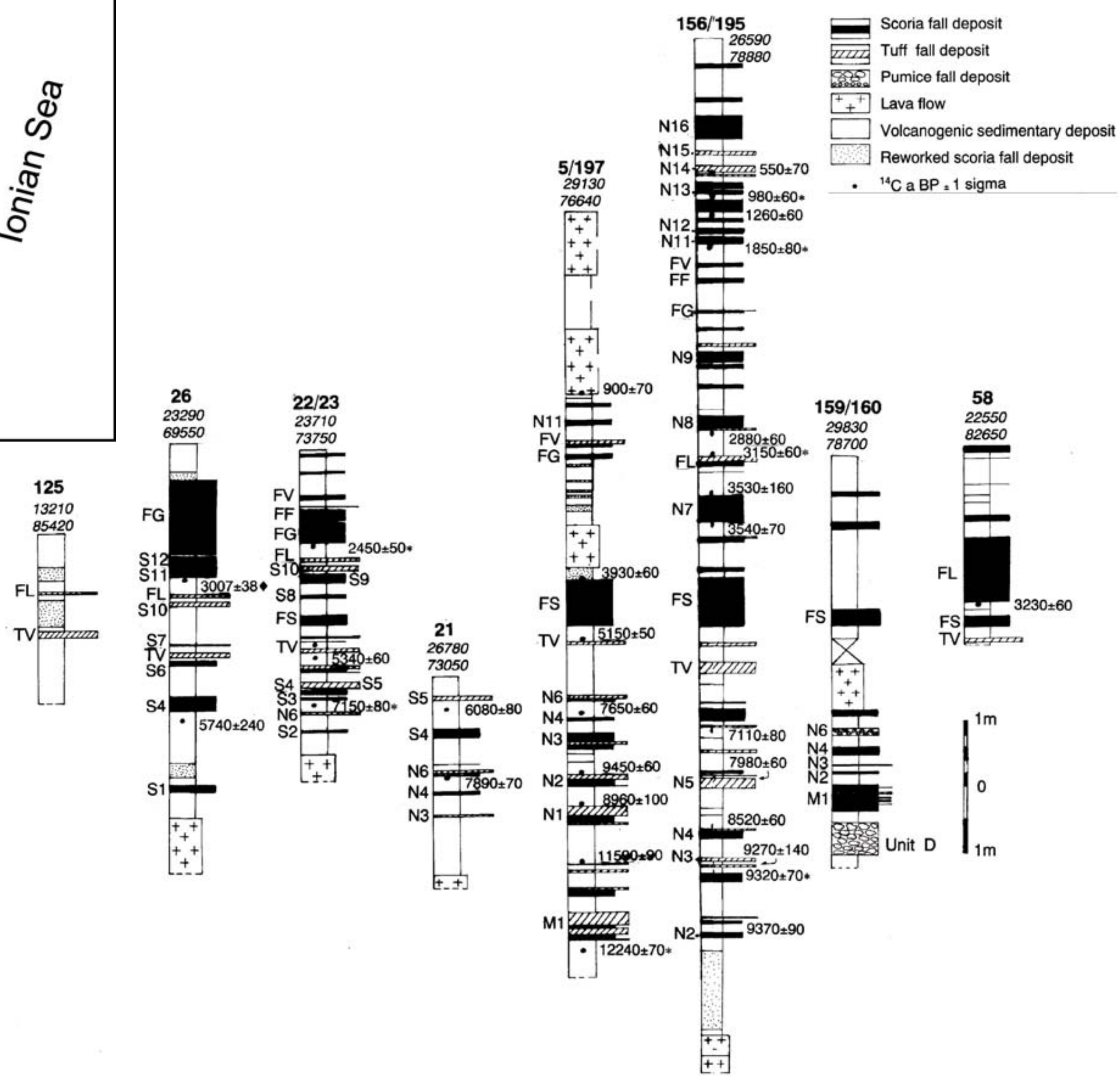


Fig. 15 - *Stratigraphic correlation of the last 12 ka pyroclastic deposits. Location of stratigraphic sections is in Fig. 14. Marker beds are labelled with letters from keywords used in the field description; these are:* M1, TV, FS, FL, FG *and* FF. *The other tephra layers are correlated at least in two sections and are labelled with S and N followed by a number (from* DEL CARLO et alii, *2004). Age with diamond is from* CORTESI et alii *(1988) and ages with stars are from other sections.*

TEPHROSTRATIGRAPHY

Stratigraphic and facies analyses demonstrate that the volcaniclastic deposits mantling the medial-distal parts of Mt. Etna's eastern flank are composed of pyroclastic layers interbedded with volcanogenic sedimentary deposits, and each tephra layer represents the product of a single explosive eruption. Tephrostratigraphy has allowed the reconstruction of a detailed framework for the complex volcaniclastic succession mantling Mt. Etna's eastern flank. It has also permitted the identification of several airfall deposits as marker beds (Figs. 14 and 15) (COLTELLI *et alii*, 2000). The latter can also be used for the stratigraphic correlation and relative dating of lava flows, which is otherwise difficult owing to their limited areal distribution.

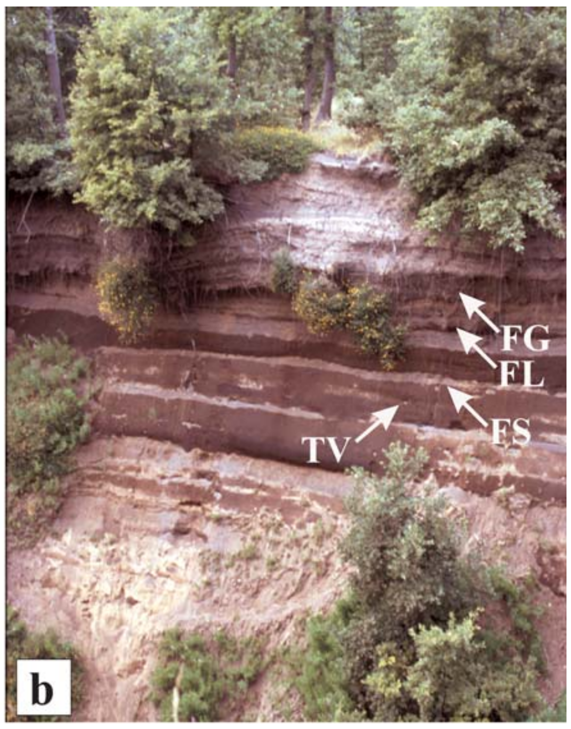


Fig. 16 - a) *View of the Casa del Fanciullo's outcrop on the NE flank of Mt. Etna, corresponding to section 156/195 in Figs 14 and 15. The Holocene pyroclastic succession unconformably overlies the flank of a parasitic scoria cone.* b) *Detail of the pyroclastic succession in which some marker beds are evidenced* (TV, FS, FL *and* FG).

The example shown is that of the Holocene pyroclastic succession (Figs. 14, 15 and 16). During the field mapping of the eastern flank, the Holocene marker beds were used to group the lava flows into several temporal intervals (Fig. 8C).

GEO-VOLCANOLOGICAL EVOLUTION

An understanding of the volcanic stratigraphy of the area, together with the identification of its main petrographic, geochemical, geomorphologic and structural features, enables the evolution of the eastern flank of Mt. Etna Volcano to be reconstructed.

Volcanic activity in the area began with fissure-type eruptions concentrated along the Timpe fault system. Effusive eruptions were first characterized by a tholeiitic transitional affinity, and their products have a radiometric age of about 225 ka (GILLOT *et alii*, 1994). Successively, the same fissural system produced alcaline-Na lavas, forming a very thick succession covering the transitional succession. This initial activity built up a large shield volcano outcropping along the Ionian coast for about 15 km.

A successive cycle of volcanic activity indicates a westward shift in the volcanic feeding system. This cycle partly maintained the fissure-type eruptive style of the previous cycle, during which a first occurrence of central-type eruptions appeared. The latter activity built up three polygenetic centres by erupting Na-alkaline lavas similar to those forming most of the Mt. Etna Volcano. After the smaller Tarderia and Rocche volcanoes, the larger Trifoglietto volcano grew (Fig. 17), forming the first important volcanic edifice in the history of Mount Etna. Moreover, three more volcanic centres, called Giannicola, Salifizio and Cuvigghiuni (Fig. 17), were formed as a consequence of limited local adjustments of the Trifoglietto Volcano feeding system. The main chemical composition of effusive products is mugearitic and benmoreitic. The products of the above-described volcanic cycle, whose inception is dated back to about 120 ka ago, are located near the south-western sector of the present Valle del Bove depression.

The next step is the growth of the Ellittico volcano, which is the largest strato-volcano inside the complex and composite volcanic construct of Mt. Etna. Fig. 17 shows the location of the feeder of the Ellittico volcano with respect to the smaller centres described previously. According to the few radiometric age determinations carried out on lavas in the Valle del Bove (TRIC *et alii*, 1994), the eruptive activity of the Ellittico began about 80-60 ka ago, and ended with a caldera collapse around 15 Ka (COLTELLI *et alii*, 2000). The activity of the Ellittico volcano developed at first as a strongly recurrent alternation of explosive and effusive eruptions, which then turned mostly effusive and ended with caldera-related explosions. The Ellittico eruptions were located in the central crater or in several parasitic cinder cones. The petrochemical character of the Ellittico lavas appears to be hawaiitic, mugearitic and benmoreitic.

The Ellittico caldera depression was partly filled by the recent, mainly Holocene products of the Mongibello volcano, which is the active expression of the Mt. Etna Volcano. Mongibello can be recognized as a large and relatively thin sheet of lavas and tephra, widely covering the older Etna products for about 85% of the total surface of Mt. Etna. Mongibello's activity is mainly related to several cinder and spatter cones scattered over the entire eastern flank of the volcano, and mostly limited, during the last decades, to the upper part of the Valle del Bove and the main summit craters. The composition of Mongibello lavas is mainly hawaiitic to benmoreitic. The volcano was dissected by the catastrophic flank collapse of Valle del Bove, that occurred about 10 ka ago, together with the emplacement of debris avalanche deposit on the eastern flank (CALVARI *et alii*, 1998; 2004). The Valle del Bove collapse produced a large amount of re-mobilized volcanic material as debris flows along the valley and a wide alluvial fan spreading into the Ionian sea. The mostly

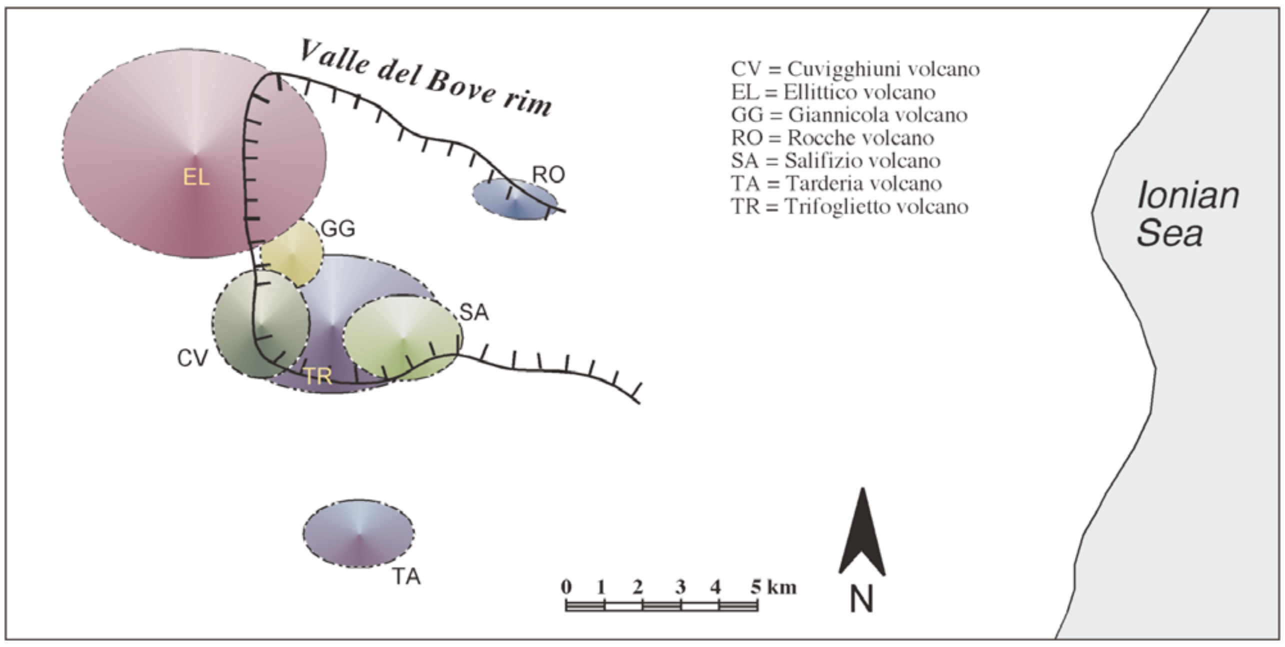


Fig. 17 - *Location sketch-map of the main volcanic centres formed during the evolution of Mt. Etna Volcano. See Fig. 6 for stratigraphic relationships.*

Fig. 18 - *Lava flow from the 2002 NE-Rift eruption destroying the Linguaglossa pinewood and the Mareneve road.*

effusive Mongibello volcano also produced violent explosive eruptions, such as the plinian eruption of 122 BC (Coltelli *et alii*, 1998), which formed the Cratere del Piano caldera on which the present summit cone of Mt. Etna Volcano was built.

LAVA FLOW HAZARD ASSESSMENT

We illustrate an example of a Geographic Information Systems (GIS) processing of a detailed geological map of an active volcano for the purposes of providing a preliminary and qualitative lava flow hazard assessment. The first basis for the assessment of volcanic hazard in volcanic areas is the record of all past volcanic activity, as provided in a detailed geological map. Geological data are combined with topographic data (Digital Elevation Model) and human settlement locations to obtain maps showing the recent behaviour of the Mt. Etna Volcano and evaluate the links between the possible future behaviour of the volcano and human activities. The geological data in Fig. 1 have been properly organised in a geographical database along with their detailed spatial and temporal informations. To each graphic element on the map, such as points, lines and polygons, a series of stratigraphic and geological attributes have been assigned, following the model suggested by the National Geological Survey of Italy (Artioli *et alii*, 1997), which was subsequently improved. In particular, we have upgraded the database structure in order to obtain a more complete relational database and a new table according to which to link different objects in various layers and relate them to an age (Groppelli & Norini, 2002). The GIS was used to represent and analyse the age, length and outcropping extent of lava flows, and the location of related vents and eruptive fractures; all these parameters were obtained or calculated from the database. GIS processing can illustrate intersections between lava flows and vent properties, hazard zones and DEM data, allowing a better definition of relationships between effusive volcanic activity, urban settlements and morphology.

For example, in order to evaluate the historical intersections between lava flows and settlements, we have performed a data cross-analysis assigning to each town or village a value corresponding to the number of lava flows which have invaded the inhabited area, including a safety margin of 300 meters from their outskirts (Fig. 19). The resulting map shows that the towns of Fornazzo and Milo are those which have had the highest frequency of lava flow invasions over the last 400 years (Fig. 19), whereas the eastern and south-eastern sectors of the study area are the safest zones because they record an interval in lava flow recurrence of over 400 years.

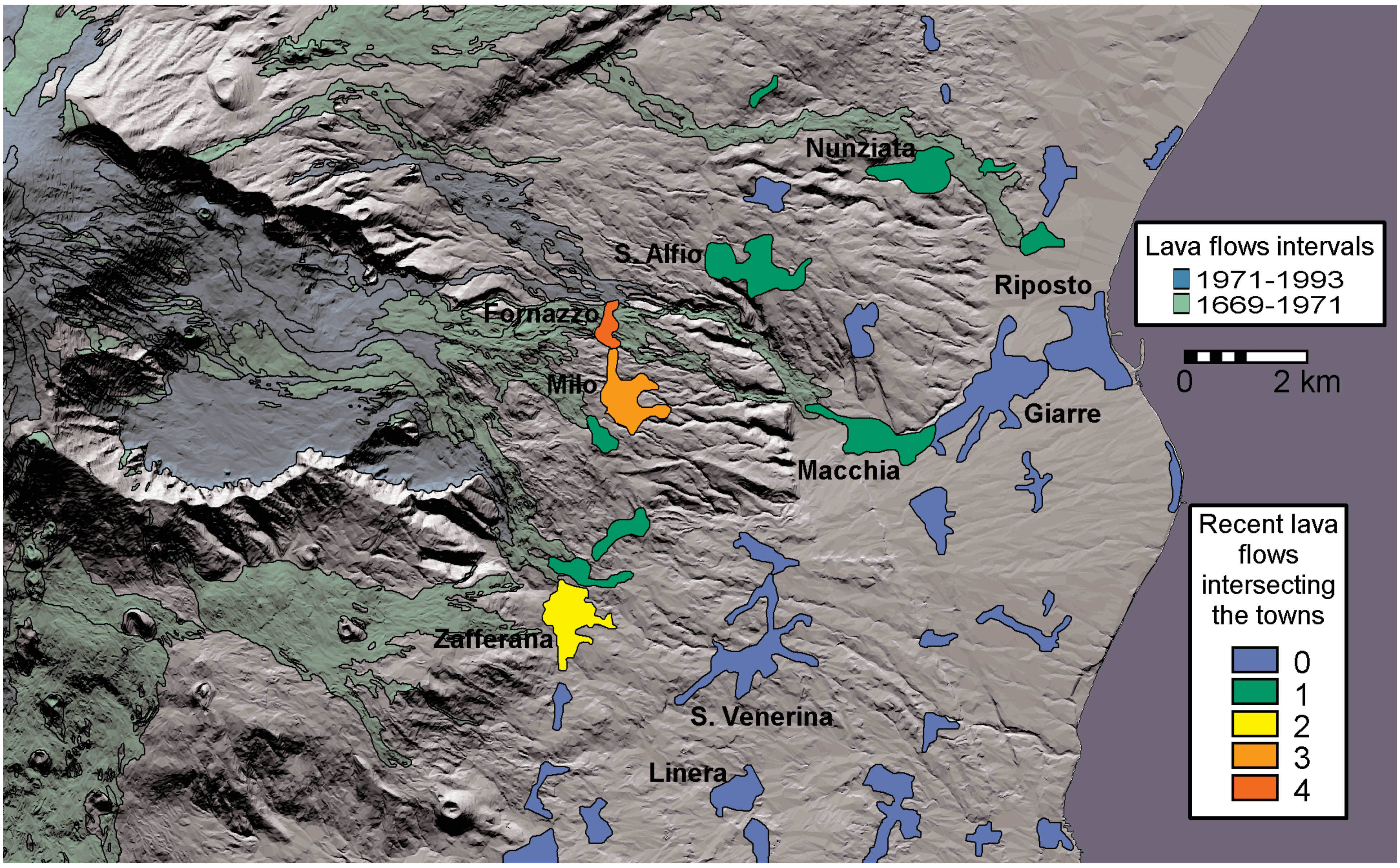


Fig. 19 - *Number of recent lava flows intersecting the main settlement areas on the eastern flank of Mt. Etna Volcano (eruptive data from 1669 to 1993 AD). GIS processing is based on the last two lava flow time intervals. The representation is on a Digital Elevation Model.*

ACKNOWLEDGEMENTS

The copyright for the Etna vector topographic data belongs to the Gruppo Nazionale di Vulcanologia - CNR (GNV-CNR). The authors would like to thank Giovanni Macedonio for the GNV vector data and for the geographical software provided for data processing. Careful reviews and suggestions by F. Lucchi and C. Tranne were greatly appreciated.

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