Geogr. Fis. Dinam. Quat.
23 (2000), 117-129, 12 figg.

ALDO CINQUE (*), GAETANO ROBUSTELLI (*) & MARIO RUSSO (**)

THE CONSEQUENCES OF PYROCLASTIC FALLOUT ON THE DYNAMICS OF MOUNTAIN CATCHMENTS: GEOMORPHIC EVENTS IN THE RIVO D'ARCO BASIN (SORRENTO PENINSULA, ITALY) AFTER THE PLINIAN ERUPTION OF VESUVIUS IN 79 AD

ABSTRACT: CINQUE A., ROBUSTELLI G. & RUSSO M., *The consequences of pyroclastic fallout on the dynamics of mountain catchments: geomorphic events in the Rivo d'Arco basin (Sorrento Peninsula, Italy) after the plinian eruption of Vesuvius in 79 AD.* (IT ISSN 0391-9838, 2000).

This paper deals with the results of a study carried out on the lowest alluvial terrace of the Rivo d'Arco stream (Sorrento Peninsula), which terminates with an active sea cliff in the Marina di Equa area. This cliff exposes a very interesting geo-archaeological section which allowed us to conduct important observations about the geomorphic events which occurred in the area soon after the Vesuvius Plinian eruption of 79 AD and during the following couple of centuries. Said events consisted of a dramatic phase of valley floor aggradation (up to 20 m) and coastal progradation (over 400 m) that were fed by debris flow and alluvial events reworking the 79 AD pyroclastic cover from the steepest parts of the catchment. This intense and short (few decades) period of deposition was then followed by one of erosion that included both the longitudinal dissection and the frontal truncation of the fan-deltaic body the previous sedimentary events had created. Due to this coastal erosion the shoreline retreated up to almost its original (i.e. pre-eruption) position in less than two centuries.

This study demonstrates that the stronge Plinian eruptions of the Vesuvius may very well have dangerous consequences on the mountainous areas surrounding the Campana Plain, not only because of damage deriving directly from the distal fallout, but also because of subsequent events of rapid downwasting of the pyroclastic mantles. This kind of hazard is particularly high in the foothill areas and especially with regard to those human settlements that are located along valley floors and on the quiescent alluvial fans of the mountain front.

KEY WORDS: Geomorphic changes, Volcanoclastic deposits, Alluvial hazard, Geo-Archaeology, Vesuvius (Italy).

RIASSUNTO: CINQUE A., ROBUSTELLI G. & RUSSO M., *Le conseguenze della caduta di piroclastiti sulla dinamica di bacini montuosi: gli eventi geomorfologici nel bacino del Rivo d'Arco (Penisola Sorrentina, Italia) dopo l'eruzione plinania del Vesuvio nel 79 dC.* (IT ISSN 0391-9838, 2000).

Durante la famosa eruzione del vesuvio del 79 d.C., la dorsale calcarea dei M.Lattari-Pen. Sorrentina ha ricevuto fino a 2m di prodotti piroclastici da caduta. Nonostante sia ancora preservata sui tratti di versanti a morfologia blanda, questa copertura risulta spesso totalmente mancante sui tratti più acclivi della dorsale i quali possono raggiungere e superare pendenze del 50%.

Allo scopo di ricostruire le prime fasi di rimozione della suddetta copertura, abbiamo studiato il terrazzo alluvionale-costiero visibile alla foce del Rivo d'Arco che drena uno dei più ampi ed acclivi bacini del versante settentrionale della dorsale.

In prossimità del lato orientale della baia di Marina di Equa si rinvengono i resti di una villa romana, costruita tra il 1° sec. a.C. ed il 1° sec. d.C.; le scale di accesso alla villa sono parzialmente sepolte dai prodotti pomicei e cineritici dell'eruzione del 79 d.C. e da depositi di versante, cui segue, in continuità di sedimentazione, una successione di depositi alluvionali. L'analisi stratigrafica dei depositi affioranti nel tratto medio-terminale del Rivo d'Arco suggerisce differenti meccanismi deposizionali afferenti alla fase di aggradazione del fondovalle. La prima è rappresentata dalla deposizione, con meccanismi di trasporto in massa, di prodotti derivanti dalla rapida rimozione della copertura piroclastica del 79 d.C. dai tratti più acclivi del bacino. Essa richiama i fenomeni franosi da scorrimento-colata rapida che tuttora ricorrono sui rilievi circostanti la Piana Campana (vedi, ad esempio le frane del 1998 sui Monti di Sarno). La successiva dissezione di detti depositi favorì poi la completa aggradazione della preesistente piana costiera e la formazione, nel tratto terminale del Rivo d'Arco, di un conoide alluvionale confinato con meccanismi deposizionali del tipo *sheet floods*; esso doveva presumibilmente estendersi verso mare di almeno 400m come si desume estrapolando il gradiente della superficie oltre la falesia che oggi lo tronca. I caratteri sedimentologici e stratigrafici del complesso, unitamente alla presenza di tracce archeologiche sovrapposte ai depositi (non più recenti della metà del 2° secolo), provano che la fase di aggradazione e progradazione durò solo alcuni decenni. Ugualmente rapidi furono lo smantellamento, ad opera del moto ondoso, della parte prominente del conoide-delta e la sua reincisione lon-

---

(*) *Dipartimento di Scienze della Terra, Università Federico II, Largo S. Marcellino 10, 80138 Napoli - Italy.*

(**) *Archeologist, Corso Italia 79, Sorrento (Na).*

This work has been supported financially by funds C.N.R. n. 98.00258.CTO05 (Prof. A. Cinque) and Cofin. MURST 1997 «Geomorphic processes response to environmental changes» (Chief scientist prof A. Biancotti; local scientist Prof. L. Brancaccio).

The Authors are grateful to Dr. Conor Sheedy for the review of the English language of the manuscript.

gitudinale ad opera del torrente. Infatti la falesia che delimita il terrazzo alluvionale reca tracce di una terza fase edilizia che, per quanto priva di elementi utili ad una datazione più precisa, va inquadrata nel periodo tardo romano (3°secolo d.C.)

TERMINI CHIAVE: Variazioni geomorfiche, Depositi vulcanoclastici, Rischio alluvionale, Geo-Archeologia, Vesuvio (Italia).

INTRODUCTION

The Somma-Vesuvius strato-volcano (topping at 1256 m a.s.l.) is situated in a large tectonic depression occupied by a coastal aggradational plain (the Campana Plain) representing the top surface of a sedimentary, volcanic and volcanoclastic infill up to 3000 m thick [Ippolito & *alii*, 1973; Brancaccio & *alii*, 1991; Santacroce (ed.), 1987]. The inner borders of the coastal plain are defined by calcareous mountains which reach up to 1500 metres a.s.l. and are delimited by Quaternary fault scarps of noticeable steepness and height. With the sole exception of hillslope elements more inclined than about 50°, the limestone reliefs surrounding the Campana Plain appear mantled by a cover of pyroclastic deposits which offers a good record of the main explosive eruption which have occurred during the Late Quaternary [Orsi & *alii*, 1996; Rolandi, 1997; Santacroce (Ed.), 1987].

Dealing in particular with the Monti Lattari ridge (which forms the Surrento Peninsula), it can be observed that the type-section of the pyroclastic mantle is composed of an upper part corresponding on the products of the Vesuvius eruption of 79 AD and a much more weathered lower part of Pleistocene age. The latter is made of superimposed layers and lenses of fine textured pyroclastics (sometimes rich in weakened pumice fragments) reflecting a number of explosive eruptions occurred in the Campana Plain during the Middle and Late Pleistocene. These ancient materials are only well preserved on the more gently sloping elements of the landscape, where they reach up to several metres of thickness; on the contrary, they are reduced to a few decimetres on the slope elements of intermediate steepness (25 to 35 degrees) and are totally lacking – or preserved only in karstic pockets and holes – on the steepest topographic elements. The yellowish to orange-brown and dark brown colours of these materials are a consequence of phases of weathering and pedogenesis occurred between eruptions. The products of the well known Plinian eruptions given by the Somma-Vesuvius between about 18.000 years ago and 79 AD are not found on the Lattari Mts. because they were dispersed in other directions (NE to SE).

The upper part of the cover is made of the products of the 79 AD Plinian eruption, which is famous worldwide as having been responsible for the burial of the Roman towns of Pompeii, Herculaneum and Stabiae. In the study area, this eruption resulted in fallout deposits, 100 to 150 cm thick, mostly made of light pumice fragments (up to 50 mm in diameter) with a subordinate lithic component (up to 30 mm in diameter). Our survey has discovered that at least the less elevated portion of the study area was also affected by an ashy pyroclastic flow; which is to be correlated with one of the surges that have been recognised in the upper part of the sections exposed in Pompeii, Boscoreale, Oplontis and Herculaneum (Surge Units S5 or S6 of Sigurdsson & *alii*, 1985).

Within the Rivo d'Arco basin, the 79 AD pyroclastic blanket shows marked lateral variations of thickness due to the variable amount of erosion it has suffered since its emplacement. As the latter is proportional to slope angle, the blanket still retains its primary thickness (or almost so) only on the most gentle landscape units (0° to 10° inclined), while it is virtually absent from scarps more than about 50° inclined, and more or less truncated on slope elements of intermediate inclinations.

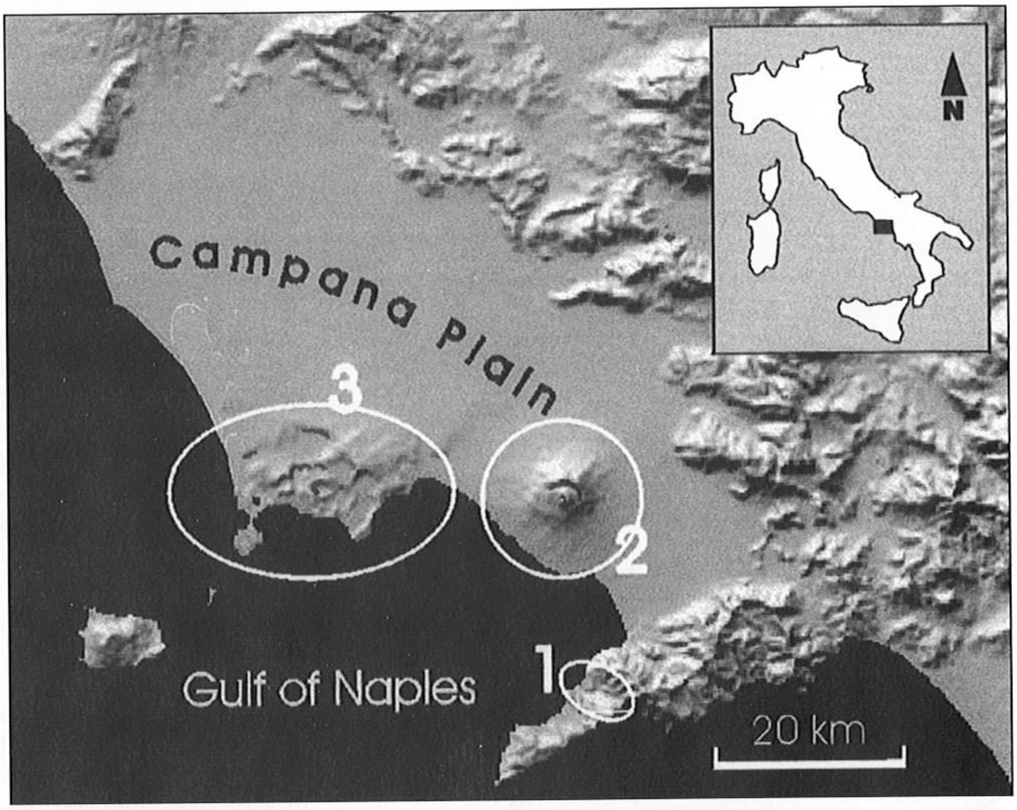
A number of well documented landslides occurred in the last few decades (Lazzari, 1954; Brancaccio & *alii*, 1999; Di Crescenzo & Santo, 1999; Guadagno & *alii*, 1999; Cinque & *alii*, 2000) coupled with field evidence of other forms of instability, give a good picture of the way the 79 AD blanket continues to be removed from the slopes 19 centuries after the eruption. It occurs both through gradual and extensive water erosion (rilling and gullying phenomena peaking at the onset of the rainy season) and through isolated landslides evolving into very wet and rapid debris flows which occur during periods of exceptionally continuous and high rainfall (Guadagno & Periello Zampelli, 2000). While this modern *scenario* sufficiently elucidates the retarded behaviour of a pyroclastic blanket in these calcareous mountains, very little is known about the mechanisms and rates of removal that may affect a fallout mantle directly after its emplacement.

In order to understand this better, we are studying a number of different local situations of well preserved erosional and/or depositional evidence of past events. Within this framework, this paper analyses the alluvial deposits that have aggraded the final reach of the Rivo d'Arco valley shortly after the 79 AD eruption and have been subsequently dissected by the stream and frontally truncated by the sea. No detailed description and interpretation of these deposits is to be found in geological literature of the Surrentine Peninsula, the only mention being the one appearing on the official geologic map of the area (Sheet n. 196 of the 1:100.000 Carta Geologica d'Italia) where those deposits are erroneously mapped as «Holocene beach deposits».

GEOMORPHOLOGY AND GEOLOGY OF THE RIVO D'ARCO BASIN

The Rivo d'Arco stream drains one of the largest catchments of the northern flank of the Monti Lattari calcareous ridge. This ENE-WSW trending ridge is one of the uplifted compartments which border the Campana Plain (fig. 1). Among the numerous volcanic centres that punctuate the depression, the most relevant for the purpose of this article is Somma-Vesuvius volcano, whose main crater is only 25 km NNE of the study area and has given several large Plinian eruptions during the last 20,000 years [Santacroce (Ed.), 1987; Rolandi & *alii*, 1997)].

FIG. 1 - Location of the Rivo d'Arco Basin (1) with respect to the Somma-Vesuvius (2) and the Phlegrean Fields (3) volcanoes.



The Rivo d'Arco basin has an area of 19,7 km^2 and a total relief of about 1400 m. As shown in fig. 2 and 3, the Rivo d'Arco stream is a 4th Order (*sensu* Strahler, 1962) water course that has a steep longitudinal profile and a catchment which is dominated by very steep slopes, especially in its eastern part. The bulk of the basin's geometry is controlled by the arrangement of fault blocks that have derived from Pliocene and Middle Pleistocene faulting phases (Caiazzo & *alii*, 1998). The highest and most evident fault scarp forms the northeastern side of the basin, and has the crest between 1100 and 1400 metres a.s.l. (Mt. Faito-Mt. Conocchia block) and an average height of 700 metres. As shown by the position of ancient marine terraces and other sea-level marks, the ridge attained a final stability during the end part of Middle Pleistocene (-Cinque & Romano, 1990), but the adjacent Campana Plain depression (Gulf of Naples included) continued subsiding even during the Late Quaternary (Cinque & *alii*, 1997).

Most of the catchement is cut into hard Cretaceous limestones, but limited portions of the middle and lower reaches of the Rivo d'Arco valley are entrenched into a Late Quaternary alluvial and pyroclastic succession (Vico Equense Unit) up to 90 metres thick. This unit is best exposed in the scarps that bound the terraces of Vico Equense and Seiano, on the right and left banks of the Rivo d'Arco respectively (fig. 4). The lower half of the Vico Equense unit is made up of crudely stratified and irregularly cemented fanglomerates which often contain weathered pyroclastics both as a matrix and intercalations. The upper part of the succession is predominantly pyroclastic and shows, near the top, a 10 to 20 metres thick welded tuff belonging to a huge eruption occurred on the Campana Plain around 36,000 yrs BP (i.e. the Campanian Ignimbrite; Orsi & *alii*, 1996). The dissection of this succession started probably shortly after the emplacement of the Campanian Ignimbrite (Cinque & *alii*, 1997), while the resulting terraces experienced another 4-5 m of pyroclastic aggradation due to the fallout of major explosive eruptions of the Phlegrean Fields volcanoes (NE of Naples) and Somma volcano (Vesuvius' ancestor).

On the slopes of the Rivo d'Arco catchement, on the other hand, the residual thickness of the Quaternary pyroclastic cover is normally a matter of decimetres (local values ranging from zero to one or two metres; according to slope angle and position). Within this blanket, the products of the 79 AD eruption are by far the most widespread ones and also the only eruption unit that has more or less well preserved primary characteristics. Previous eruption units, when present, are weathered into andosols and show truncated and/or reworked profiles. On the other hand, the fallout events linked to Vesuvian eruptions of the last two millennia have negligible thickness and appear incorporated in the modern soil (Di Gennaro & *alii*, 1995).

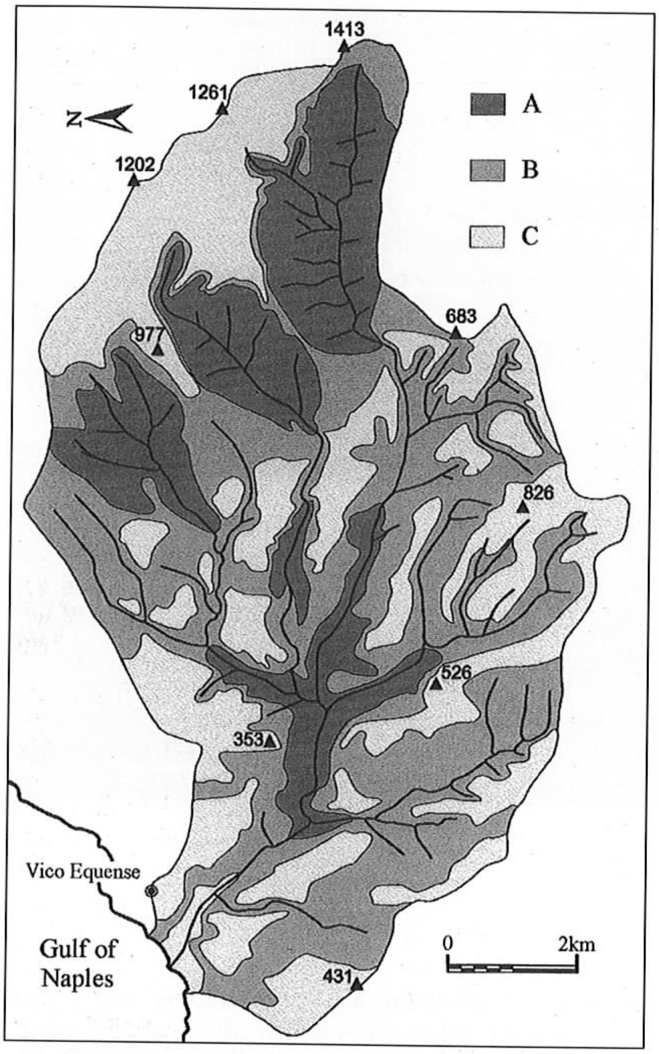


FIG. 2 - Clivometric classification of the Rivo d'Arco Basin. A) Slopes steeper than 30° rich in elements that exceed 45°; B) Slope elements 15° to 30° inclined; C) slope elements gentler than 15°.

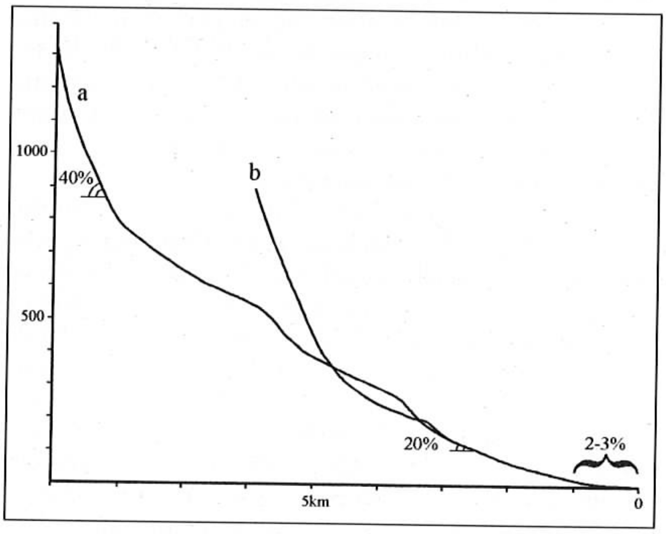


FIG. 3 - Longitudinal profile of (a) the deep V-shaped Rivo d'Arco valley and (b) one of the branches descending from Mt. Faito.

The fertility of these soils and their very high water retention capacity permit the existance of extensive woodland cover (beechland above 900-1000 m; mixed deciduous forest or man-selected horse chestnut woodland between 900 and 500 m; mainly olive trees plantations and residual patches of the original Mediterranean *maquis* below 500 m).

The study area has a humid Mediterranean climate subtype with cool and wet winters and hot and dry summers. The annual rainfall varies between 800 mm on the coast and about 1400 mm on the highest summits. Most of the rainfall is concentrated between October and May, with a peak in early Autumn and another in Spring. The rainfall intensity is highly variable and it includes days with more than 100 mm of precipitation with an average recurrence time of a decade or so. Extreme events of some tens of millimetres per hour have also been recorded.

THE EQUA ALLUVIAL TERRACE AND ITS DEPOSITS

The lowest alluvial terrace of the Rivo d'Arco stream (hereinafter referred to as Equa Terrace) is well developed along the terminal reach of the watercourse. It is some 400 m wide near the coast, where it terminates with an active sea cliff of about 7 m. Towards the interior, the width of this terraced surface gradually narrows untill it disappears at about 600 m from the river mouth, where the valley takes a V shaped cross-profile. However, other small relics of the Equa Terrace have been found inland up to about 1.2 km from the river mouth (fig. 4).

The sediments forming the terminal portion of the Equa Terrace are well exposed only along the sea cliff, while no exposure is available along the stream banks because they are protected by walls (parts of which date back to the Roman times).

The succession exposed in the sea cliff only shows its lowermost terms at the NE extreme of the Equa bay where its base rises above the sea level due to the gentle ramp it forms at the base of the scarp descending from the Vico Equense terrace (fig. 5). Here both the limestones of the Cretaceous substratum and the ruins of a Roman sea-side villa appear covered by the products of the 79 AD Vesuvian eruption. These includes a basal fallout deposit made of pumice and lithic fragments, followed by ashes which are partly due to fallout and partly due to a pyroclastic flow. The latter facies shows sandwave bedforms and consists of thin, low-angle cross-bedded ash layers alternating with massive ash beds rich in accretionary lapilli. This is the most distal outcrop of surge deposits reported to date for the 79 AD eruption and it had to cross some 20 km of sea to reach here from Mt. Vesuvius. Therefore it can be related with one of the strongest surges of that eruption; most likely with the event occurred in the morning of 25 August 79 AD (Unit S6 of the type-sections of Sigurdsson & *alii*, 1985), which was probably the same that caused the death of Plinius the Elder while he was trying to leave Stabiae (7 km NE of Vico Equense) by boat.

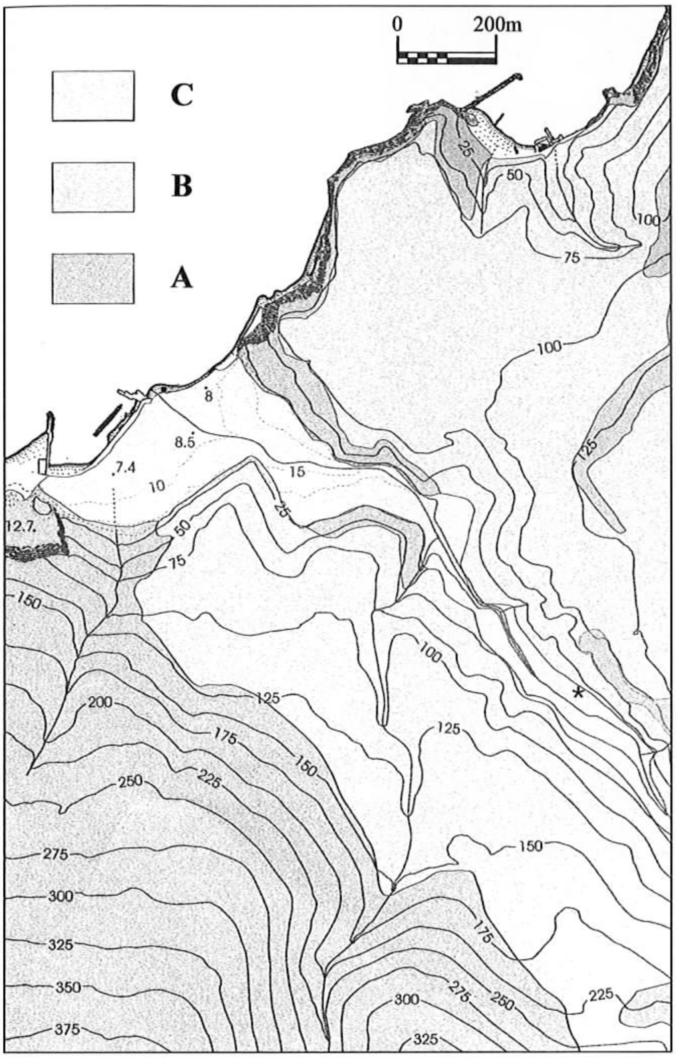


FIG. 4 - Geologic sketch map of the study area: A) Cretaceous limestones; B) Vico Equense Unit (Late Quaternary); C) Equa Alluvium (Holocene); *) Inner outcrop of Equa Alluvium.

As better illustrated in Chapter 4, the above mentioned Roman villa shows three phases of construction. The first phase structures, which are not older than the 1st century BC, can be easily distinguished from younger ones both on the base of the building materials and techniques and because they locally disappear under the products of the 79 AD eruption. This first villa was constructed on the calcareous slope bordering the bay, and it had a partly covered staircase descending to the beach (fig. 6). On the ruins of this, the in situ products of the 79 AD eruption are followed by a tongue of crudely stratified slope deposits (up to 1.5 m thick) that reworks the same AD 79 pyroclastics and also includes pebbles derived from the Pleistocene conglomerates of the Vico Equenze Terrace, angular fragments from the Cretaceous substratum and pieces of Roman Age masonry materials as well. The sub-horizontal alluvial beds that form the Equa Terrace onlap these slope deposits and form the entire height of the sea cliff further to the SW.

However, by removing the sands of the modern beach from the very base of the sea cliff, we were able to ascertain that, in the vicinity of the ruins, the pyroclastic and alluvial succession rests on a unit made of well rounded gravel and sands, rich in femic minerals of Vesuvian origin, that we have interpreted as the upper beachface of 79 AD This unit reaches up to 0.5 m a.s.l. and disappears from the sea cliff toward the SW, suggesting that, before the eruption, the bay was more rotund than the present one.

The Roman beach deposits are followed by residual patches of 79 AD pyroclastics (no more than few decimetres thick) and by a debris flow unit (up to one metre thick) composed of the same pyroclastic materials plus isolated fragments of Roman tiles, bricks and other building materials. The remaining part of the succession exposed in the sea cliff (5 to 6 m thick) is composed of waterlaid deposits which are also dominated by the products of the 79 AD eruption, eventhough appreciable concentrations of non-volcanogenic materials (limestone pebbles and cobbles; fragments of plaster, bricks and tiles) locally occur.

As already pointed out, it has been difficult to find other good exposures of the Equa Terrace sediments inland. However, a small relic observed at about 1.2 km from the river mouth (hereinafter and in fig. 4 called «inner outcrop») revealed a succession composed of a discontinuous basal layer of 79 AD pumiceous fallout (up to 1 m thick), followed by at least 15 metres of reworked products from the same eruption.

In the following sections we first describe the single lithofacies shown by the Equa Alluvium and then their associations and significance. The adopted lithofacies codes are those of Mathison & Vondra (1983) as amended by Smith (1987), who described new criteria and erected new code names for the alluvial deposits influenced by explosive volcanism. The textures, fabrics and sedimentary structures of these sediments are similar to those described by Smith (1987) and Maizels (1993) for sheet-flood and debris flow deposits.

LITHOFACIES

In this paragraph we first describe the stratified facies that characterises the coastal outcrop (i.e. the long transversal section offered by the sea cliff) and then the massive facies characterising the *inner outcrop* inside the valley.

Sandstone and pebbly sandstone deposits

A first sandstone facies (*Sh*) consists of volcanoclastic debris with a fine fraction made of femic minerals (mostly augite and olivine), and a pebbly fraction consisting of lava, tuff and limestone fragments. It is organized in tabular sheets up to 10 cm thick and up to 15 m wide (fig. 7; low-

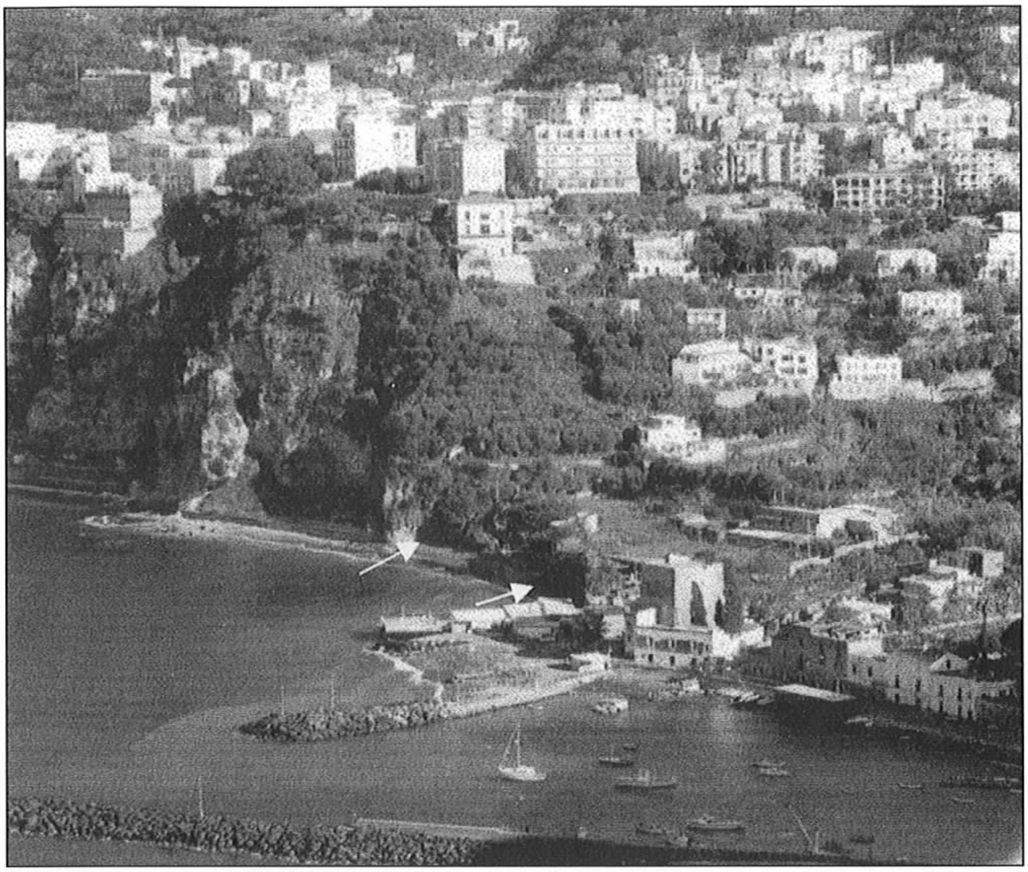


FIG. 5 - Marina di Equa bay; the arrows indicates the best exposures of Equa Alluvium along the sea-cliff.

er part). Such sheets are made of coarse-grained and pebbly sandstones with gradational interstratal contacts and common occurence of isolated out-sized clasts (*a*-axes>3cm). The pebbly, sandstone beds are normally or inverse-to-normally graded. These characters, together with the lack of trough cross-bedding, suggest for this facies a rapid deposition from sandy hyperconcentrated flood-flows (*sensu* Smith, 1986).

The second sandstone facies (*Ss*) consist entirely of volcanoclastic materials, very similar to those of the first one.

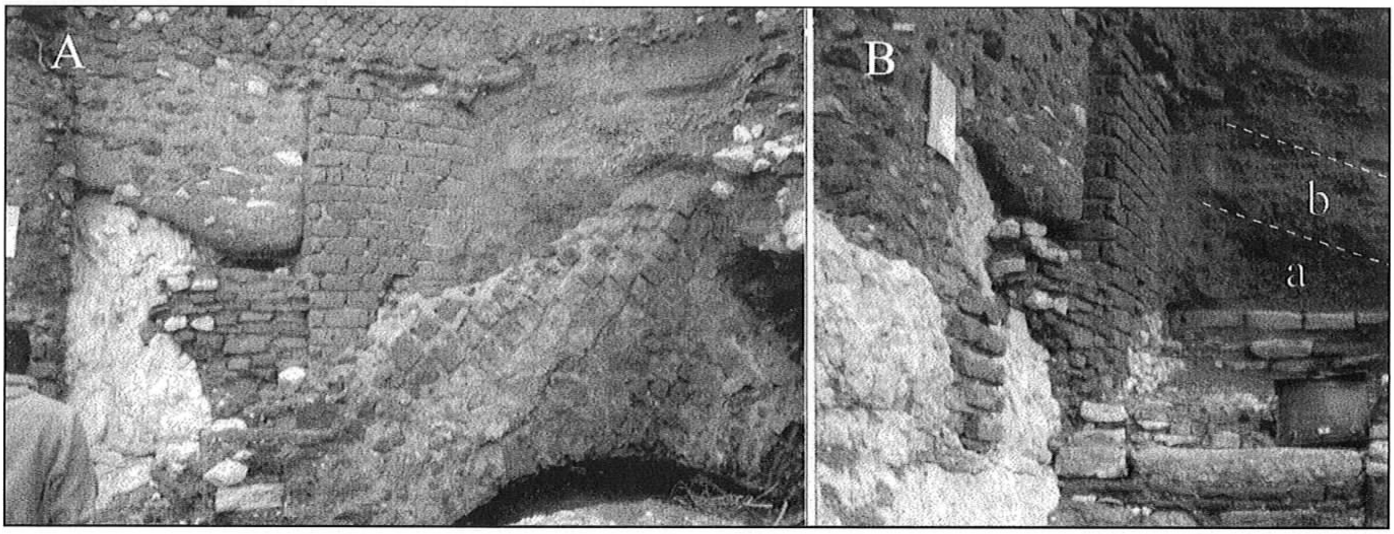


FIG. 6 - Lateral (A) and front (B) views of the staircase descending to the beach from the Roman villa. Note also *in situ* products of AD 79 eruption (a) followed by crudely stratified slope deposits (b) and the *opus reticolatum* with larger and small elements.

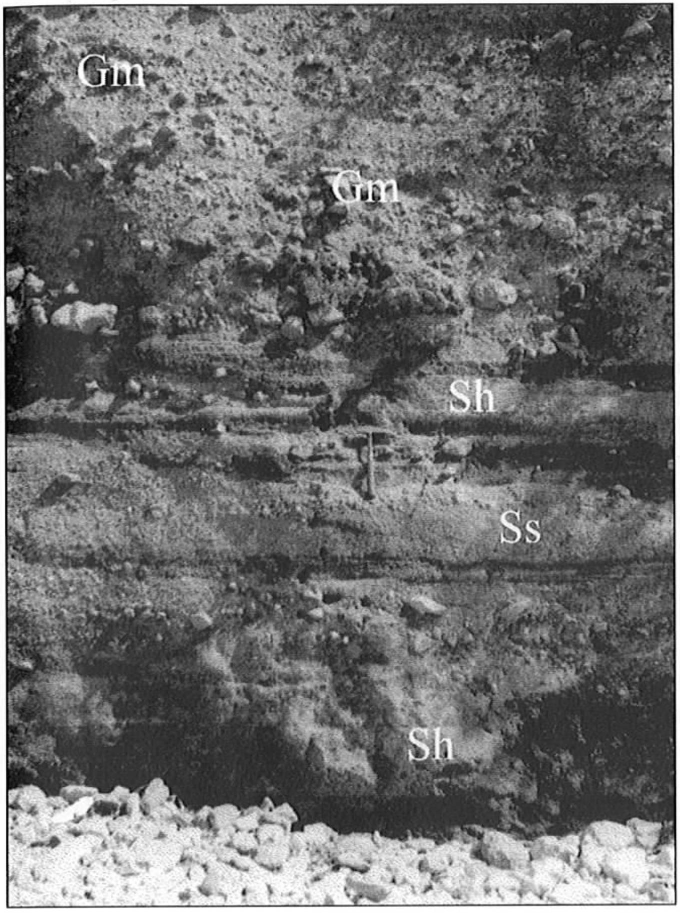


FIG. 7 - Facies association *Aa* (section normal to paleoflow direction). Note the C.U. sequence made up of a basal part consisting of sandstone deposits (*Sh* and *Ss* lithofacies) which grade upward into conglomeratic deposits (*Gm* lithofacies).

It has a typical scour-fill bedding with low-angle, onlapping laminae showing a lateral (transversal to palaeoflow) decrease in inclination. This facies consists of coarse-grained sandstone and sometimes contains pebbly lenses. Following the interpretation proposed by Smith (1988) for similar sedimentary structures, we attribute these coarse-grained sand sheets to high discharge, shallow sheet-flows.

Conglomeratic deposits

A first conglomerate facies consists of angular to subrounded limestone pebbles and/or cobbles in a matrix of sandy to fine-gravelly texture and volcanoclastic nature. It appears poorly sorted, crudely normal-graded and poorly imbricated (fig. 7; upper part). A large proportion of this facies consists of crudely stratified and clast-supported conglomerates (*Gm*). Large pebble and fine cobble clasts are oriented with *a*-axes transverse to the presumable palaeoflow direction (SE to NW). For the above listed characteristics and the absence of sandstone lenses, this facies has been interpreted as the product of gravelly, hyperconcentrated flood-flows.

A second conglomerate facies (*Gms*) is massive and matrix-supported. Its clasts range in size from a few centimetres to up 20 cm and exibit a poor degree of rounding, as well as a tendency for long *a*-axes to be parallel to palaeoflow direction. Such lithofacies sometimes outcrops as small debris-flow deposits filling scours around 30 cm deep and up to 50 cm wide, cut chiefly into the stratified sandy facies.

Pumice rich and pelitic deposits

From the textural point of view, the pumice rich facies is made up of clast-supported, moderately to well sorted conglomerates consisting of rounded pumice fragments, no more than 1 cm in diameter, in an abundant sandy and silty matrix. These sediments are organised in tabular sheets few centimetres thick and up to 20 m wide. These characteristics individuate a *Gm* type facies, but we prefer to put a *P* before the acron (which thus becomes *PGm*) to underline the pumiceous nature of the clasts, which enabled their deposition together with much finer materials because of their low specific weight.

The *PGm* facies alternates locally with both *Sh* type sediments and a greenish-grey, pelitic facies which is characterised by well developed horizontal laminations (*Fl*) and seems to represent the waning stages of the same flows that brought the *PGm* and *Sh* deposits (fig. 8).

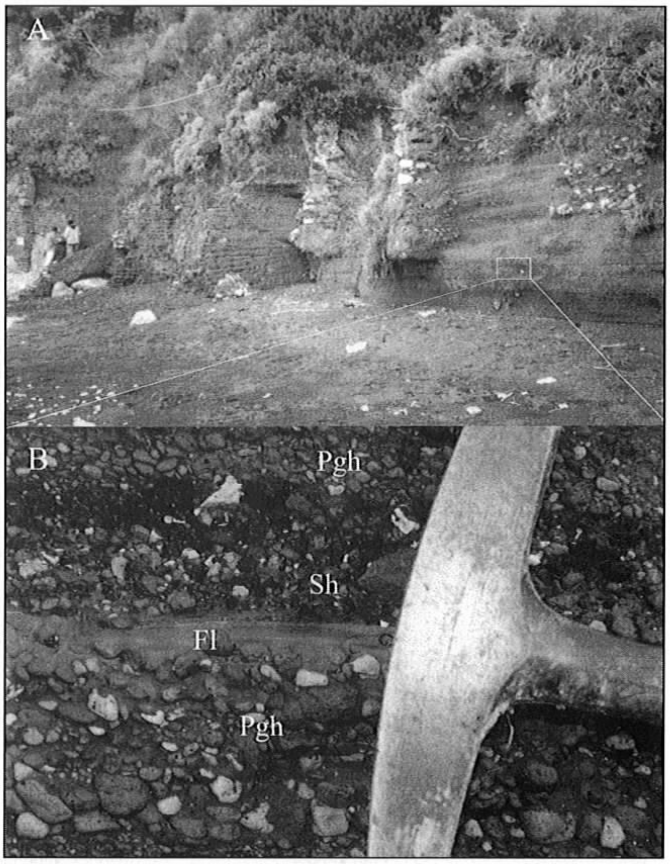


FIG. 8 - Facies association *Ab* (section normal to paleoflow direction). Note also (A) the building remnants and (B) details of the facies association *Ab* showing *Pgh, Fl* and *Sh* lithofacies alternating.

Massive deposits

In terms of texture, these deposits consist of grey, massive conglomerates which are supported by a silty matrix (volcanic ash) representing about 40% of the total volume (*Dd* lithofacies). The clasts are subangular fragments of white and light grey pumices, scoria and lava, with a minor percentage of baked *ejecta* of Mesozoic limestone (fig. 9). All these components are typical of the 79 AD fallout (Sigurdsson & *alii*, 1985) and also their size ranges reflect those of the primary product of that eruption (diameters up to 3 cm for the pumices and up to 1 cm for the lithics). Isolated limestone pebbles and cobbles deriving from the local substratum also occur. They are angular in shape and their long axis orientation is mainly parallel to the paleoflow.

FACIES ASSOCIATIONS AND DEPOSITIONAL SETTING

Two main facies associations (*Aa* and *Ab*) can be distinguished within the transversal section of the plain visible in the sea cliff. The *Aa* association is restricted to the area closer to the Rivo d'Arco mouth (fig. 7). It consists of a coarsening, upward sequence which starts with sandy hyper-concentrated flood-flow deposits (*Sh*) interbedded with rare, scour-fill, cross-bedded sandstone's (*Ss*) and debris-flow deposits (*Gms*). Subordinate, small lenses of PGm and Fl are also present. These facies grade upward into gravely hyper-concentrated flood-flow deposits (*Gm*) which are organised in lenticular units up to 50 cm thick and 15 to 20 m wide in the cross section. The *Ab* association (fig. 8) characterises the portion of the sea cliff closer to the Roman ruins. It consists of an almost monotonous sequence of broad sheets of pumice-rich conglomerates (*PGm*) alternating with pelitic (*Fl*) and sand sheets (*Sh*).

These two facies associations grade laterally into each other (fig. 10), giving rise to a number of intermediate situations. For example, roughly midway between the river mouth and the ruins, the exposed sequence is made of broad sheets of sandstone (both *Sh* and *Ss*) alternating with pumiceous conglomerates (*PGm)* and pelitic intervals (*Fl)*, which overlie the debris flow deposits (*Dd*), today exposed thanks to recent winter sea storms (fig. 9).

The facies association *Aa* seems to represent the axial portion of an alluvial cone forming mainly because of sheet floods (tens of them) whose deposits were locally remoulded by small waning stage channels. The association Ab can be attributed to a more peripheral (lateral) portion of the alluvial cone which was only reached by thinner and less powerful floods.

Taking into account the well known, high sensitivity to weathering of volcanic ashes and pumices, the lack of signs of pedogenesis between the various flood units, leads us to believe that the temporal gaps between flood

FIG. 9 - Debris flow deposits (lithofacies *Dd*) exposed (A) close to the inner relic and (B) in the lowermost part of the sea cliff. Note also (B) the *Gms* lithofacies filling a paleochannel cut into debris flow deposits and grading upward to *Sh, Pgh* and rare *Gm* lithofacies alternating.

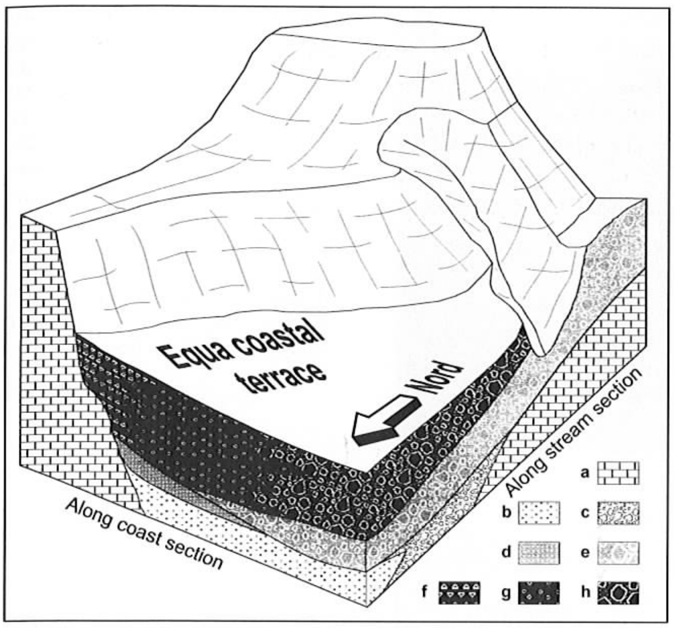


FIG. 10 - 3D sketch of the stratigraphical relationships among the units forming Equa coastal terrace. a) Substratum (Cretaceous limestones and late Quaternary deposits); b) Roman beach deposits; c) Roman coastal plain deposits; d) AD 79 pyroclastic deposits; e) Debris flow deposits (facies *Dd*); f) Slope deposits; g) *Ab* facies association; h) *Aa* facies association.

events were very short; probably of the order of months or years. On the other hand, the evidence that the volcanic material carried by the floods had suffered no appreciable weathering before being eroded, leads us to conclude that the Equa alluvial body was formed soon after the 79 AD eruption.

As far as the *inner relic* of Equa Terrace is concerned, its associate deposits have characters that suggest a debris-flow mechanism of emplacement. Appreciably, they seem to belong to a single, huge debris-flow which descended from the upper catchment as a wet mixture of all the components of the 79 AD eruption plus some calcareous clasts entrained by the moving mass while passing over pre-existing colluvial deposits. In this case the fresh state of the pyroclastic materials also demonstrates that the reworking occurred soon after the eruption, if not during it.

THE ROMAN RUINS AND THEIR RELATIONSHIP WITH POST 79 AD GEOMORPHOLOGICAL CHANGES

As already stated in Section 3, the ruins of the Roman villa occurring at the north-eastern extreme of Equa Bay show three different phases of building. The first one can be framed between the 1st century BC and the 1st century AD because it includes *opus vittatum* and *opus reticolatum* masonry works. The former became widespread during the Augustan Age whilst the latter was used in central and southern Italy between the 1st century BC and the 1st century AD (Adam, 1984) and is typical in the Surrentine Peninsula during the Augustan Age. The fact that the *opus reticulatum* appearing in the staircase of the first building phase (fig. 11; see also fig. 6) is composed of relatively large elements (about 12x12 cm) suggests a time closer to the beginning of the above mentioned period.

The villa belonging to the first phase was severely damaged by the 79 AD eruption and the remnants of the staircase descending to the beach of that time were covered by a volcanic-sedimentary complex made of (i) the fallout and surge deposits of that eruption, (ii) slope deposits representing an early phase of reworking of the 79 AD pyroclastics and (iii) the Ab facies association of the Equa Alluvium (which grades south-westward into the Aa facies association of the same formation (fig. 10).

The second phase of building occurred when the coastal plain had already been aggraded by about six-seven metres of new debris-flow and alluvial deposits. By using graphics to extrapolate the slope of the Equa terrace toward the NE, we estimate that said aggradation was accompanied by a progradation that took the coastline at least 400 m beyond the position it occupies today.

The masonry works done during the second phase included the restoration of some of the rooms already present on the calcareous slope (i.e. the north-eastern flank of the bay) and the extension of the compound with rooms constructed anew onto the adjacent plain. From the relationships between the remnants of the first and the second building phases, it appears clear that when the latter was carried out, the old staircase was completely hidden underground by the Equa Alluvium. Among others, this conclusion is supported by the fact that the walls of the second phase are not in line with the remnants of the first phase structures, which – if visible – would have been exploited as good foundations. From a geomorphological point of view, this clearly indicates that the surface of the Equa Terrace had already formed and the surface itself extended northward much more than today.

The foundations of the walls built during the second phase (well exposed because they are cut by the modern sea cliff) appear laid into trenches excavated in the Equa Alluvium (fig. 11). Judging from the building materials and the techniques used (*opus reticulatum* with small elements) the second construction phase seems to be attributed to the first half of the 2nd century. In fact, the use of the *opus reticulatum* continued up to the initial and middle part of the 2nd century (latest examples during the Antonino Pio Age; 138-161 AD), when it was replaced by bricks. Further proof that the post-79 AD phase of aggradation lasted only a few decades is given by the existence of relics of Roman walls along the entrenched terminal reach of the

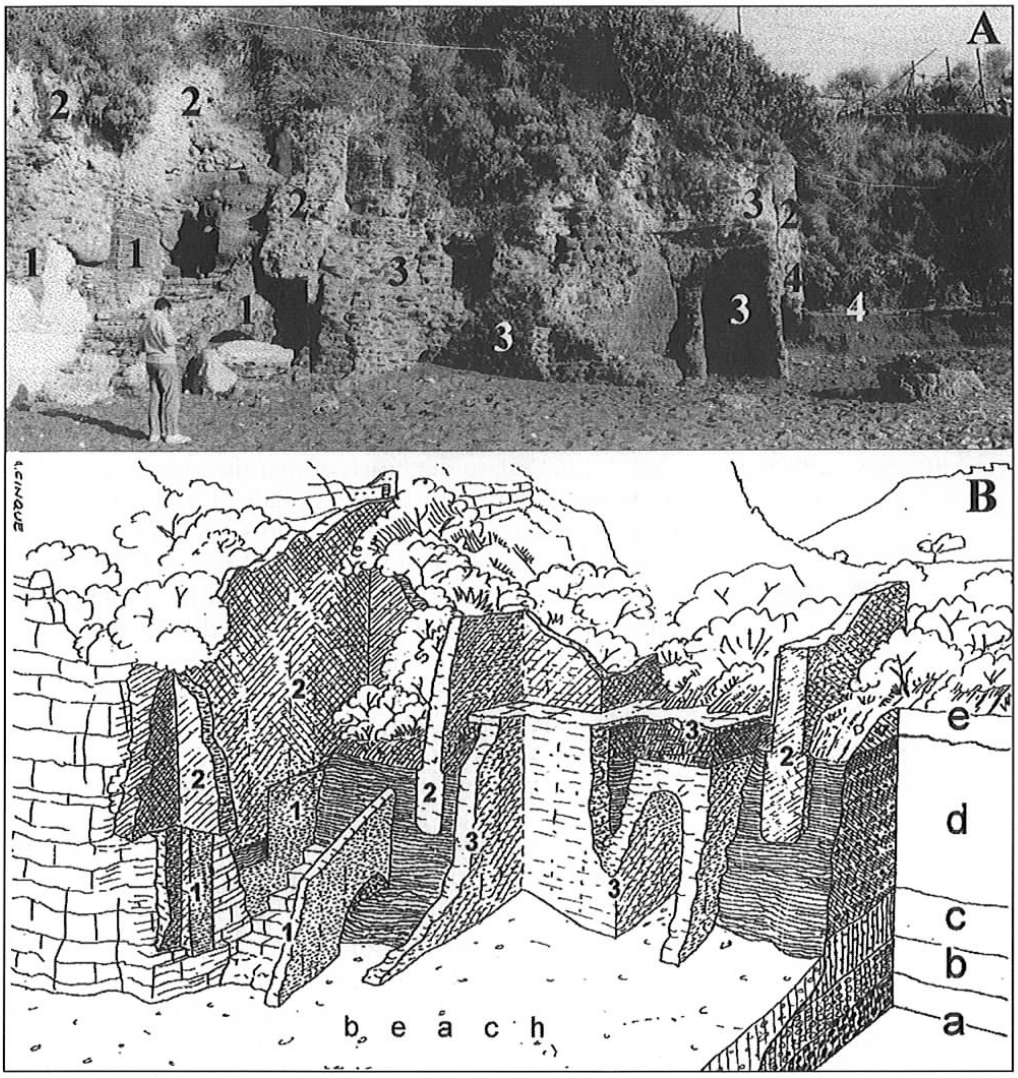


FIG. 11 - Front view (A) and simplified representation (B) of the relationships among the Holocene deposits and the Roman ruins (a: beach deposits of the 1st century AD; b: AD 79 ash deposits; c: debris flow deposits; d: pyroclastic-alluvial deposits of the 1st-2nd century AD; e: younger colluvium; 1, 2, 3: remnants of the three phases of building occurred between the 1st century BC and 3rd century AD; 4: remnants of the 4th phase of building of Middle Ages period?).

Rivo d'Arco stream. The one we have seen cannot be dated more precisely, but Mingazzini & Pfister (1946), who surveyed the area before the construction of the modern concrete walls, noted a protection wall along the incision made in *opus reticulatum*. Evidently the Rivo d'Arco had already passed to dissect its terminal fan during the second century.

The 3rd building phase, which we recognised in the Marina di Equa ruins, consists of some restoration and adaptation works to the rooms resting on the terrace and the construction of a new way down to the beach, contained within an inclined tunnel (fig. 11) departing from the rooms and emerging in the sea cliff. Moreover, the works included the construction of a room near sea level (fig. 11). It occupied the space between the old staircase (by then re-exhumed by coastal erosion) and the tunnel. As this room has been largely destroyed by waves, it is difficult to infer its original function. Although some architectural characters suggests that it was a coastal *ninfeo*, we cannot exclude that it was simply a storeroom.

However, the third building phase demonstrates a time when the prominent portion of the post 79 AD terminal fan-delta of the Rivo d'Arco had already been destroyed by the sea and the resulting sea cliff had retreated, almost to its present position. Judging from the architectural forms and the materials used (shape and size of blocks, kind of mortar, etc.) we conclude that the third phase of building probably occurred during the 3rd century.

Finally, it is worth underlining that the presence of other remnants of a subsequent phase of building occurred, probably in the Middle Ages, and are visible by way of a substructure underlying the foundations of the 2nd phase (fig. 11) and some wall foundations built to surround water-tanks.

CONCLUSIONS

Based on the above reported data and observations, we can reconstruct that the huge Plinian eruption of Mt. Vesuvius which occurred in 79 AD had severe consequences on both slope and fluvial dynamics of the Rivo d'Arco basin, with some consequences on the coastline of the mouth zone.

As can be seen both from literature data (Sigurdsson & *alii*, 1985) and from field evidence, the eruption in question caused the slopes of the Rivo d'Arco basin to be covered by a 100 to 200 cm thick fallout mantle. Its basal portion consists of 80 to 150 cm of very light, pumice fragments up to 50 mm in size and subordinate lithic fragments up to 25 mm wide. The last decimetres of the cover are made of volcanic ash emitted during the final phreatomagmatic phase of the eruption. As stated here for the first time, the least elevated part of the catchment was also invaded by a surge that left from a few centimetres to a few decimetres of ash rich in accretionary lapilli.

Thanks to the chronological constraints offered by the Equa archaeological remains, it can be stated that the alluvial deposits forming the Equa Terrace represent the effects of the very first and fastest phases of downwasting of the 79 AD pyroclastic mantle from the hillslopes of the catchment. Also, judging from the geomorphology of other valley systems of the Lattari Mts. in which we discovered relics of similar deposits (e. g. some tributary trunks of the Rio di Gragnano, the Canneto gorge near Amalfi, the Reginna valley near Scala and the Praia valley near Agerola) we can argue that the phenomena of valley floor aggradation immediately after the 79 AD eruption occurred only in those catchments whose head slopes are dominated by elements steeper than 40 degrees.

In the case of the Rivo d'Arco, such steep elements are concentrated in the tributary branches dissecting the Mt. Faito fault scarp (fig. 12), whose heads and flanks actually have very high average gradients and frequent subvertical cliffs. From the most inclined parts of these landforms (which had to appear treeless or almost so[1]) the loose fallout deposits had probably started sliding during the course of the eruption, forming taluses and cones on the valley floors. With the following day's and year's rains also the cover that was resting on relatively gentle slope elements (maybe up to 35°), probably generated numerous debris flows due to an increase of weight and sheer stress and/or gullying. As demonstrated by equivalent phenomena still sporadically occurring in the region today (Del Prete & *alii*, 1998; Guadagno & *alii*, 1999; Guadagno & Perriello Zampelli, 2000; Cinque & *alii*, 2000) these pyroclastic debris-flows are so rich in water that they do not easily come to rest when they reach the floor of a V-shaped valley. On the contrary, when the latter has enough longitudinal gradient (as the upper reaches of the Rivo d'Arco have) they continue to flow down the valley at high speed until they reach the piedmont area or a gently inclined valley reach. Along this channelled run, the passage of debris-flows may also be able to trigger many new landslides by undermining the valley sides so as to grow bigger.

We hypothesise that similar events were responsible for the accumulation of the massive facies found in the Rivo d'Arco valley and near the coast at the base of Equa Alluvium. As suggested by the perfectly unweathered state of its pyroclastic components, it was deposited by debris-flows which occurred shortly after the eruption. Roughly during the same span of time, the first Roman villa near Equa beach, already ruined by the eruption, received some minor debris flows from the slope at the back.

The subsequent tendency of the Rivo d'Arco was to dissect the debris-flow deposits occupying its gorge-like medium reach, and to deposit the resulting load further downstream in the form of a confined alluvial fan. The consequent aggradation of the pre-existing coastal plain (equal to about 6 metres near the present coastline) was accompanied by a progradation that can be estimated to be at least 400 metres by extrapolating the gradient of the Equa terrace up to the sea level.

The constraints offered by the archaeological data indicate that the growth of the terminal fan occurred in no more than a few decades. Moreover, the lack of pedogenetical layers within the alluvial sequence suggests an uninterrupted growth, while the number of elementary flood units in the sea cliff section is such as to suggest an almost annual recurrence.

It is probable that the most advanced part of this alluvial body had deltaic characters (although poorly developed due to the high rate of growth), but this cannot be proved as the distal facies of the fan have been eroded by the sea. As the archaeological constraints suggest (age of the 3rd building phase), the coastal retreat of at least 400 metres occurred within no more than 150-200 years. On the other hand, the longitudinal dissection of the Equa Alluvium - which was enhanced, if not actually created, by the sea cliff retreat - also occurred in the 2nd century because the first reinforcements of the river banks were made in *opus reticolatum*.

The period of coastal retreat started when the solid coastal discharge of the Rivo d'Arco decreased below the equilibrium with wave erosion power. This probably happened when the greatest part of the debris-flow deposits occupying the narrower portions of the valley had already been eroded away. The fact that the retreat of the sea cliff substantially stopped around the end of the 2nd century can be interpreted as the achievement of a coastline perfectly bevelled to the two calcareous promontories that delimit the Equa bay, but also the construction of protective barriers and the fast cementation capacity of the Equa Alluvium probably played a role in finally stabilising the sea cliff.

---

[1] *There is field evidence that before the AD 79 eruption, the steepest portions of the Lattari Mts had very little to no pyroclastic cover and soils because the ash and pumices thrown onto them by eruptions occurred thousands of years before had been eroded away.*

FIG. 12 - The steep slopes drained by a tributary branch of the Rivo d'Arco (M. Faito fault scarp).

REFERENCES

ADAM J.P. (1984) - *L'arte di costruire presso i Romani.* Longanesi, Milano, 1988.

BRANCACCIO L., CINQUE A., ROMANO P., ROSSKOPF C., RUSSO F., SANTANGELO N. & SANTO A. (1991) - *Geomorphology and neotectonic evolution of a sector of the Tyrrhenian flank of the Southern Apennines (Region of Naples, Italy).* Zeit. Geomorph. N.F. Suppl.-Bd. 82, 47-58.

BRANCACCIO L., CINQUE A., RUSSO F. & SGAMBATI D. (1999) - *Osservazioni geomorfologiche sulle frane del 5-6 Maggio 1998 del Pizzo D'Alvano (Monti di Sarno, Campania).* «Studi Geografici e Geologici in onore di Severino Belloni», a cura di G. Orombelli, 1-37, Glauco Brigati, Genova.

CAIAZZO C., CINQUE A. & MEROLA D. (1998) - *Cronologia relativa e cinematica delle faglie appenniniche ed antiappenniniche della Penisola sorrentina.* Atti del 79° Congr. Soc. Geol. It., Palermo, 21-23 Settembre 1998.

CINQUE A., AUCELLI P.P.C., BRANCACCIO L., MELE R., MILIA A., ROBUSTELLI G., ROMANO P., RUSSO F., RUSSO M., SANTANGELO N. & SGAMBATI D. (1997) - *Volcanism, tectonics and recent geomorphological change in the bay of Napoli.* Suppl. Geog. Fis. Dinam. Quat., III, t.2, 123-141.

CINQUE A., ROBUSTELLI G., SCARCIGLIA F. & TERRIBILE F. (2000) - *The dramatic cluster of pyroclastic debris flows occorred on 5-6 May 1998 on the Sarno mountains (Vesuvius regions, southern Italy): a geomorphological perspective.* In: Bromhead E., Dixon N. & Ibsen M.L. (eds.), «Landslides in research, theory and practice». Vol. 1, 273-278, Telford, London 2000.

CINQUE A. & ROMANO P. (1990) - *Segnalazione di nuove evidenze di anitche linee di riva in Penisola Sorrentina (Campania).* Geogr. Fis. Dinam. Quat., 13, 23-36.

DEL PRETE M., GUADAGNO F.M. & HAWKINS A.B. (1998) - *Preliminary report on the landslides of 5 May 1998, Campania, Southern Italy.* Bull. Eng. Geol. Env., 57, 113-129.

DI CRESCENZO G. & SANTO A. (1999) - *Analisi geomorfologica delle frane da scorrimento-colata rapida in depositi piroclastici della Penisola Sorrentina (Campania).* Geogr. Fis. Dinam. Quat., 22, 57-72.

DI GENNARO A., D'ANTONIO A., INGENITO M.R., LULLI L., MARSEGLIA G., TERRIBILE F. & TODERICO L. (1995) - *I suoli della provincia di Napoli.* Camera di Commercio, Industria, Artigianato ed Agricoltura, CUEN, 137 pp.

GUADAGNO F.M., CELICO P., ESPOSITO L., PERRIELLO ZAMPELLI S., PISCOPO V. & SCARASCIA MUGNOZZA G. (1999) - *The Debris Flows of 5-6 May 1998 in Campania, Southern Italy.* Landslide News, 12, 5-7.

GUADAGNO F.M. & PERRIELLO ZAMPELLI S. (2000) - *Triggering mechanisms of the landslides that inundated Sarno, Quindici, Siano, and Bracigliano (S. Italy) on May 5-6, 1998.* In: Bromhead E., Dixon N. & Ibsen M.L. (eds.), «Landslides in research, theory and practice». Vol. 2, 671-676, Telford, London 2000.

IPPOLITO F., ORTOLANI F. & RUSSO M. (1973) - *Struttura marginale tirrenica dell'Appennino campano: reinterpretazione di dati di antiche ricerche di idrocarburi.* Mem. Soc. Geol. It., 12. 227-250.

LAZZARI A. (1954) - *Aspetti geologici dei fenomeni franosi verificatisi nel salernitano in conseguenza del nubifragio del 25-26 Ottobre 1954.* Boll. Soc. Natur. Napoli, 63, 131-142.

MAIZELS J. (1993) - *Lithofacies variations within sandur deposits: the role of runoff regime, flow dynamics and sediment supply characteristics.* Sedim. Geol., 85, 299-325.

Mathison M.E. & Vondra C.F. (1983) - *The fluvial and pyroclastic deposits of the Cagayan basin, northern Luzon, Philippines-an example of nonmarine volcanoclastic sedimentation in an interarc basin.* Sedimentology, 30, 369-392.

Mingazzini P. & Pfister F. (1946) - *Forma Italiae. Regio I, Latium et Campania, II, Surrentum.* Sansoni, Firenze.

Orsi G., De Vita S. & Di Vito M. (1996) - *The restless, resurgent Campi Flegrei nested caldera (Italy): constraints on its evolution and configuration.* J. Volcanol. Geotherm. Res., 74, 179-214.

Rolandi G. (1997) - *The eruptive history of Somma-Vesuvius.* In: Cortini M. & De Vivo B. (eds.) «Volcanism and Archaeology in Mediterranean area», Publ. By Research Signpost., Trivandrum (India), 77-88.

Santacroce R. (ed.) (1987) - *Somma-Vesuvius.* C.N.R., n. 114, vol. 8, Rome, Italy.

Sigurdsson H., Carey S., Cornell W. & Pescatore T.S. (1985) - *The Eruption of Vesuvius in AD 79.* Nat. Geogr. Res., 1(3), 332-387.

Smith G.A. (1986) - *Coarse-grained nonmarine volcanoclastic sediment terminology and depositional process.* Geol. Soc. Am. Bull., 97, 1-10.

Smith G.A. (1987) - *The influence of explosive volcanism on fluvial sedimentation: the Deschutes Formation (Neogene) in central Oregon.* J. Sedim. Petrol., 57, 613-629.

Smith G.A. (1988) - *Sedimentologt of proximal to distalvolcanoclastics dispersed accross an active foldbelt: Ellensburg Formation (late Miocene), central Washingtown.* Sedimentology, 35, 953-977.

Strahler A.N. (1964) - *Quantitative geomorphology of drainage basins and channel networks.* In: Chow V.T. (ed.) «Handbook of Applied Hydrology». Section 4-II, McGraw-Hill, New York.

(ms. received 1 April 2000; accepted 15 September 2000)