Giornale di Geologia Applicata 1 (2005) 103 –112, doi: 10.1474/GGA.2005-01.0-10.0010

The Rock of Orvieto (Umbria, Central Italy)

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ABSTRACT. Orvieto, about 100 km north of Rome, was built by the Etruscans on a massive rock of limited extension, a relict left by the erosion of the Alfina tuffaceous plateau. The latter was produced in the Pleistocene by the magmatic activity of the "Vulsin Apparatus" in northern Latium. The bedrock of the Rock of Orvieto is composed of Plio-Pleistocene marine clays which, owing to their high erodibility, represent a sinking *substratum*, causing falls and topples which have affected the edges of the cliff since historical times. Along with the installation of a complex monitoring system of piezometers, inclinometers and extensometers stationed along all the cliff edge, stabilization works were carried out, consisting of nails, anchors (passive in the upper portion and active in the basal portion of the Rock), drain pipes and waterproofing works for avoiding water infiltration into the rocky mass.

Key terms: Geomorphology, Landslides, Orvieto, Umbria.

Introduction

The town of Orvieto is in the province of Terni (Central Italy), about 100 km north of Rome, standing on the northern edge of a broad volcanic plateau from the Quaternary period (Alfina plateau) that covers all of northern Latium, crossing over the border into Umbria (FIG. 3).

Orvieto (from the Latin *Urbs Vetus*, or "old town") owes its particular character to the fact that it was built - by the Etruscans in the 9th-8th century BC - on a Rock of limited extension (approx. 1.3 km^2) which is one of the relicts left by the erosion of the Alfina tuffaceous plateau (FIG. 1). Because of the way it is built, this historic town is very vulnerable, made highly unstable due to natural causes, essentially the landslides which have occurred for centuries along the edges of the Rock, reducing its area over time and constituting a direct threat to the historic center and its splendid monuments (FIG. 2).

Fig. 1 – Panoramic view of the Orvieto's Cliff.

Fig. 2 – The front of the Orvieto's Cathedral, one of the most important monuments of the Gothic architecture in Italy.

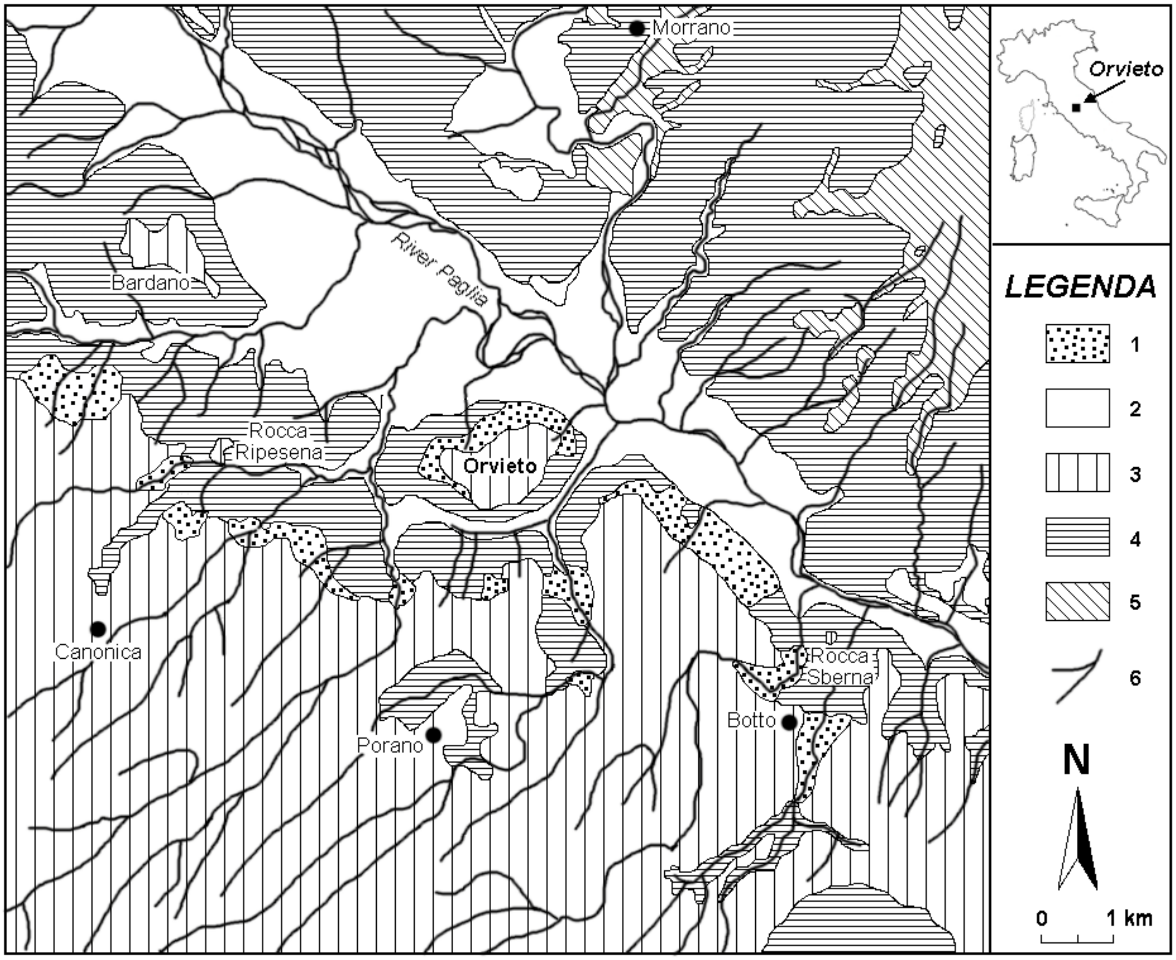

Fig. 3 – Geological sketch of the Orvieto area, at the boundary between Latium and Umbria (central Italy). LEGENDA: 1) talus (Olocene); 2) recent and present alluvial sediments, also terraced (Olocene - Upper Pleistocene); 3) volcanic rocks of the Alfina Plateau (Middle Pleistocene); 4) gravels, sands and clays (marine clastic sediments, Lower Pleistocene – Pliocene); 5) marls and sandstones (pre-Pliocenic bedrock); 6) River Paglia and its main tributaries.

The Orvieto case differs only marginally from other towns of the same region (Bardano, Rocca Ripesena, Rocca Sberna, Civita di Bagnoregio) which developed in similar morphological conditions and, as a consequence, currently show similar instability phenomena (PANE & MARTINI, 1997).

Orvieto was included in the list of towns to be consolidated entirely with State funds by Royal Decree no. 1067 of 4 March 1937. Since that date and up to the present, a number of works have been carried out for the consolidation and stabilization of the Rock, which have made it possible to protect and preserve it. In particular, the worsening of the instability processes led to the passing of a national law (230/78 and subsequent amendments) for urgent consolidation works on the Rock to protect its historic-artistic heritage.

The present study, which falls within the activities of the special Technical-Scientific Commission established by the Region of Umbria following the enactment of Law no. 545 of 1987 as the advisory board for consolidation works ("Permanent Observatory for the Monitoring and Maintenance of the Rock of Orvieto" - Conversini et al., 1996), illustrates the geological, geomorphological, and hydrogeological characteristics that lie behind the instability of the Rock and the town of Orvieto, as well as the consolidation works which have been done and their current monitoring network. Its aim is to avoid the possibility of further landslide phenomena which might threaten one of the most important historic centers of ancient origin in Italy.

Geological description of the Rock of Orvieto

Geological-structural configuration

The current geological configuration of the Orvieto area is the result of neotectonic and volcanic events taking place in the Quaternary period. The substratum of the volcanic plate of the Alfina plateau is composed of Pliocene marine clays; when the sea had definitively receded from the area, it underwent an extensional tectonic stage during the Lower Pleistocene (CATTUTO et al., 1994). This resulted in a normal fault (FIG. 4-a) striking approximately NW-SE, the raised block of which acted as a "wall" against which the volcanic magma flows and pyroclasts of the "Apparato Vulsino" accumulated. These are what form the Alfina plateau, dating from the Middle Pleistocene.

The Paglia river, one of the most important tributaries of the Tiber River which currently flows at the foot of the tuffaceous Rock of Orvieto, cut its bed in a selective manner, along this line of tectonic displacement. The tuffaceous plate thus remained progressively raised in relation to the lowering of the Paglia valley and increasingly farther from the main course of the river (FIG. 4-b).

At the same time that the Paglia river was cutting its valley, its tributaries on the right "dismembered" the large tuffaceous plate, often through regressive erosion phenomena (FIG. 4-c). This is still well preserved and cut off toward the SW, while toward the NE it is progressively reduced into *mesas* (such as Bardano and, of course, Orvieto), which may reach the dimensions of isolated pinnacles, or *buttes* (such as Rocca Ripesena or Rocca Sberna).

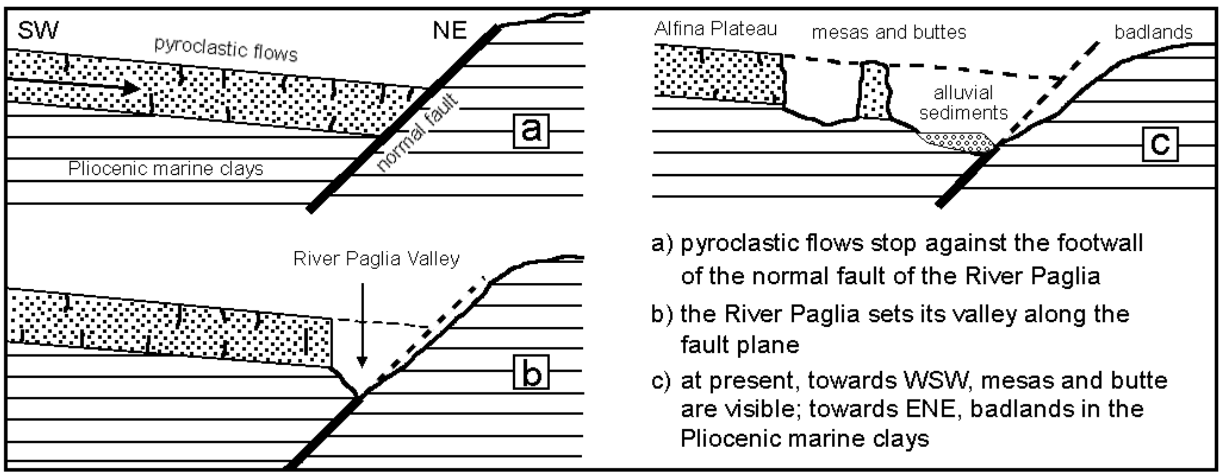

Fig. 4 – Schematic evolution of the Orvieto's area during Quaternary age. From CATTUTO *et alii* (1994), modified.

Stratigraphic characteristics

In detail (PIALLI et al., 1978; CONVERSINI et al., 1995), the stratigraphic sequence of the area is characterized, from the lower layers up (FIG. 5), by marine clays, followed by a sequence in fluvial-lacustrine facies of limited thickness ("Albornoz Series") and finally by the tuffaceous plate which constitutes the Rock itself.

The basal clays

Clays constitute the base of the stratigraphic sequence in the entire Orvieto area. Attributed to the Middle Pliocene, due to their malacological and microfossil content they have a bluish color, tending toward gray and toward yellowish if altered. The $CaCO_3$ content is relatively high (marly clays), and in some areas is even greater than 40% (argillaceous marls). They also have a good percentage of micaceous silt, which gives them a characteristic luster. Their structure is in large, massive banks, in a sub-horizontal position. They are overconsolidated and thus frequent fissuring appears.

The clays can be seen cropping out on the slopes of the Orvieto hill up to the base of the tuffaceous plate. The geometry of their roof, deduced from mechanical and geoelectrical drillings, shows a general inclination toward NNE, with a very gentle slope in the eastern part of the town, and a steeper slope in the western part.

The "Albornoz Series"

Following the clays in a slight angular unconformity is the "Albornoz Series," which can be seen cropping out on both the WSW side of the Rock and also on the side facing ENE. This series, which is in a fluvial-lacustrine facies, dates to the Lower Pleistocene. It has a limited thickness (max. 15 meters) and is composed, from the bottom upwards, of:

- a sandy-conglomerate layer, which contains blocks of basaltic lava and is formed mainly of arenaceous and calcarenitic pebbles in an imbricate structure (thus sedimented through the action of tractive currents);
- a layer of nut-brown calcareous silts, containing altered pumice cinders and fresh water gastropods;
- a layer of white limestone with diatoms and black pumice-type cinders. The presence of diatoms and fresh water fossils in this and the preceding layer unmistakably indicates a lacustrine environment;
- a layer of pumiceous clasts, with a poor ash matrix, which marks the transition to the actual tuffaceous plate.

There are very few outcrops of this series lying between the basal clays and the tuffaceous cliff (heads of the Civetta and Salto del Livio Gullies, Porta Maggiore, Porta Romana, St. Zero). Underground, however, all the drillings done through the tuffaceous plate have found the complete series.

The Tuffaceous Plate

As mentioned earlier, the tuffaceous plate is an erosion relict situated at the edge of the broad “Alfina plateau” produced by the volcanic activity of the “Apparato Vulsino” roughly 315,000 years ago. The Rock of Orvieto, made up of pyroclastites generally of a trachyte-phonolite composition, is the result of the cooling of a high temperature pyroclastic flow, partially hardened immediately after being deposited. Evidence of this is seen in the two distinct facies which characterize the Rock: the first has a more marked stony appearance (sillar facies), with sub-vertical fissures from cooling and a reddish-yellow color; the other (“pozzolana”) can be traced to a loose mass, blackish-grey in color and without evident fissuring. The two facies are distributed in an inhomogeneous manner along the perimeter of the Rock, varying from one zone to the next without spatial continuity (CONVERSINI et al., 1995).

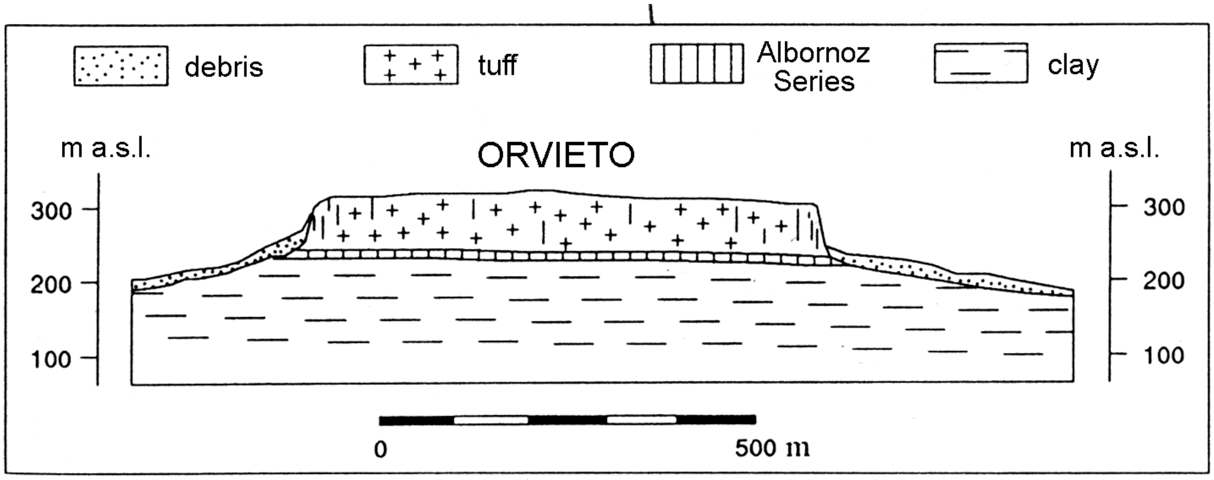

Fig. 5 - Geological schematic section of the Orvieto Cliff (from CONVERSINI *et alii*, 1995, modified).

The lithoid facies is more easily identifiable, as it is generally characterized by more abundant fissuring and by prisms with typical columnar fracturing (of primary origin, due to contractions from cooling of the pyroclastic material, FIG. 6). The pozzolana facies, instead, had less fracturing and typical erosional forms (*“tafonature alveolari”*, AMBROSINI & MARTINI, 1995).

On the top of the Cliff, at the eastern edge, there is a limited outcrop of travertine, in lacustrine facies, very stratified, spongy, and containing numerous remains of plant origin. This modest outcrop is the remains of what was surely a much larger deposit, which extended toward the SSW.

Fig. 6 – The Rock of Orvieto before the stabilization works. You can note the columnar fracturing affecting the tuffaceous mass (photo by P. Marconi).

Lastly, layers of detrital deposits produced by the mechanical weathering of the Rock surround its entire perimeter and are variously distributed on the slopes, whose substratum consists of the basal clays. The detritus is composed of tuffaceous elements highly variable in size, immersed in a pozzolana and ash matrix; the larger sized blocks are generally found along the northern slope of the Rock.

Geomorphologic characteristics

The tuffaceous cliff upon which Orvieto rises has a fairly elliptical shape, with the longer axis oriented in a ENE-WSW direction (FIG. 7). Its position is sub-horizontal, with vertical or sub-vertical walls, the highest along the southwestern side. It is 1500 meters long, about 700 meters at its widest point, and between 40 and 70 meters thick. The Rock lies on the summit of a hill which has gently inclined slopes (15°-18°) and is smoothly joined by a broad covering of detritus with the alluvial plain lying before it, formed by the Paglia river. Locally, there are deep gouges along the sides of the cliff, up to a maximum of 10-15 meters deep, produced by gullies that flow across the clayey substratum, whose heads reach the upper edge of the Rock (Salto del Livio Gully, Civetta Gully, St. Zero Gully, St. Benedetto Gully and Cavaiene Gully).

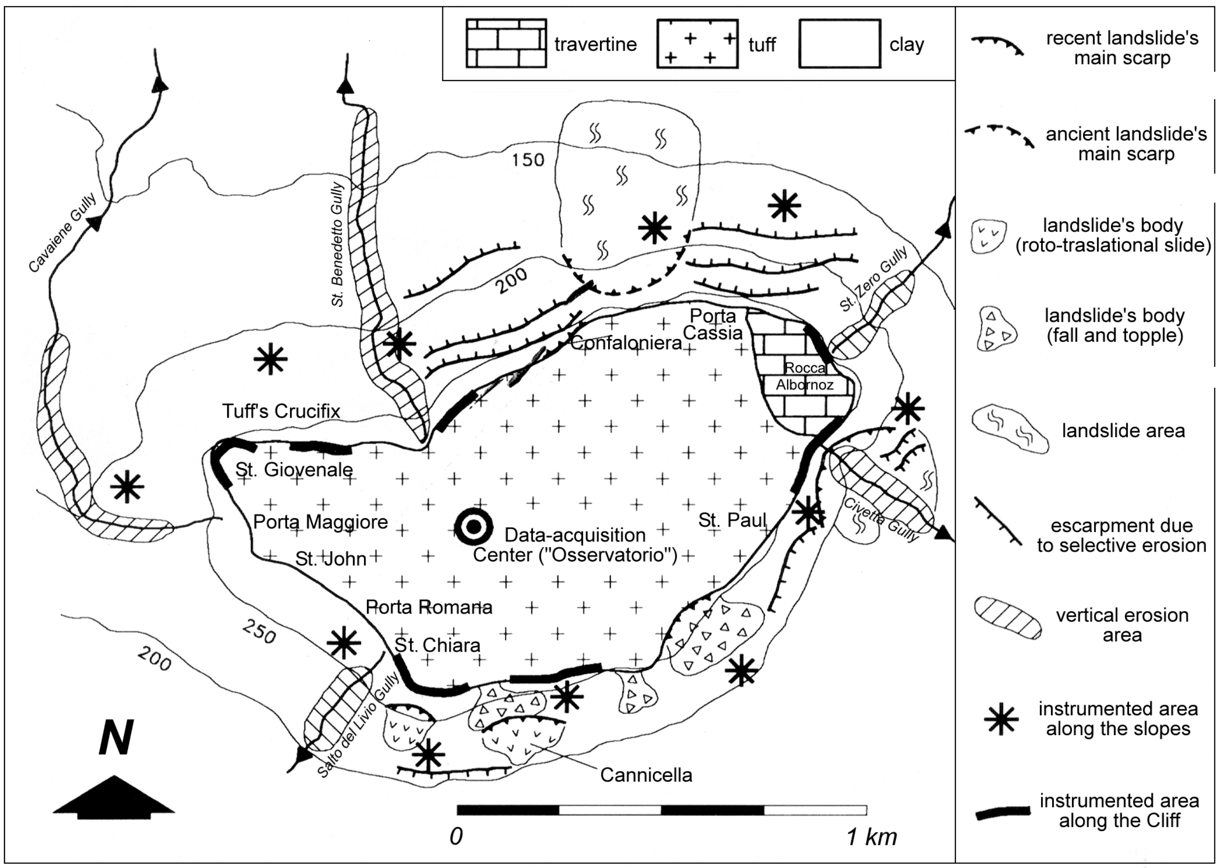

Fig. 7 – Schematic geomorphological map of the Rock of Orvieto. From CONVERSINI et alii (1995), modified.

Hydrogeological and hydrological characteristics

Hydrogeological features

The formations and the clastic deposits of the Rock of Orvieto (Albornoz Series, tuffaceous plate, travertines at the summit and tuff detritus) are permeable from porosity or from fracturing; the basal clays, on the other hand, have such low permeability that they can be considered to be practically impermeable. The different degrees of permeability affect the circulation of groundwater. The meteoric water passes through the upper rock, and is stopped when coming into contact with the basal clays. Thus a continuous water table is formed which feeds various springs, located here and there around the perimeter of the hill. In general two spring levels can be identified: one in contact with the Albornoz and the basal clays, and thus very near to the tuffaceous wall; the other scattered along the slopes of the hill, in the morphologically lowest areas or wherever the detritus-basal clay contact has been uncovered (CONVERSINI et al., 1995).

In 1978, thirty-one springs were counted; their overall flow was calculated at approximately 8 l/s, for a total of 252 m^3/year. Recent investigations have shown that this value is compatible with the amount of precipitation in the Orvieto area, confirming the validity of the proposed hydrogeological model. The chemical composition of the water allows them to be classified as bicarbonate-calcic-alkaline, characterized by a high nitrate content (well above the levels of natural groundwater), which is undoubtedly due to man's millenary occupation of the Rock of Orvieto.

Hydrological features

The five major gullies that furrow the slopes of the Hill of Orvieto are fed by both meteoric water (coming from the top) and by the springs located at the foot of the tuffaceous cliff and along the slopes of the hill. As is to be expected, their catchment areas are quite small: the largest is that of the St. Benedetto Gully, which covers an area of about 1.5 km^2. Their discharges are quite variable and depend essentially on the amount of precipitation, which averages 870 mm/year (this result was obtained from the data in the hydrological annals for the 1921-1966 period).

The uncontrolled flows of meteoric water have increased the erosion processes over time, and have brought about the receding of the river heads and the undermining of the foot of the tuffaceous cliff, thus triggering landslides. In the plains areas, instead, there are frequent episodes of inundations and flooding, especially in connection with severe storms (a 1965 storm had the heaviest rainfall ever recorded, which reached a peak of 105 mm/hour). The streams flooding most often were the St. Benedetto Gully and the Cavaiene Gully, along their final stretch just before they empty into the Paglia river (CONVERSINI et al., 1995).

Landslide phenomena

Landslide types

The general picture of the instability of the Hill and Rock of Orvieto is closely connected with the lithological characteristics of the two morphological entities. Along the slopes of the hill, which are made up of basal clays covered by an extensive layers of detritus, landslide movements result from rotational and translational slides, which can involve the two rock types separately or together. A typical example of this type is the Porta Cassia landslide, which was first reported in 1904 and covers an area of about 2.5 hectares, with a sliding surface depth varying from 3-4 meters up to 10-11 meters. The main cause of these landslides is to be found in the saturation processes of the detritus layers or of the most superficial parts of the basal clays. This saturation is connected with the presence of the water table described earlier.

Along the perimeter of the tuffaceous plate, however, the rock failure mechanisms are many and can be traced to: the lowering of blocks along the upper edge, falls or toppling of blocks in the middle-upper part, and the basal fracturing of prisms of various sizes (FIG. 8).

The rock failure mechanisms of the Rock are closely connected with the fracturing of the tuffaceous mass, very evident along all of its perimeter, which is the result of the cooling stages of the high- temperature pyroclastic flow. The instability processes are due to the different deformability of the plate compared to the underlying clays, to the high state of stress at the foot of the tuffaceous wall, and to the alteration of the mechanical characteristics of the rock types due mostly to atmospheric agents.

Added to these causes are anthropic activities, linked to the millenary presence of man, who exploited the tuff of the Rock for use as a building material. Also significant are the concessions issued by the local authorities for the extracting of pozzolana from inside the Rock, resulting in the excavating of the caves which characterize subterranean Orvieto today.

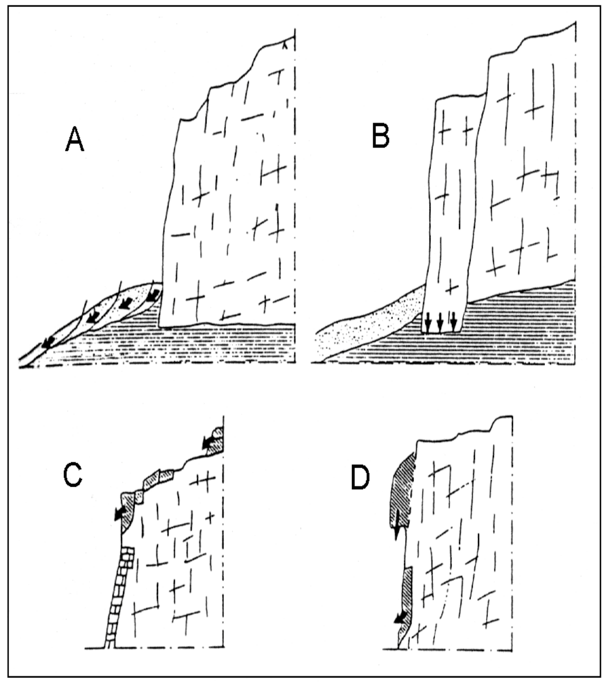

Fig. 8 – Main mechanisms of instability of the Rock of Orvieto: A) rotational slides at the toe; B) lowering of marginal slices; C) toppling and rolling; D) fall and basal rupture (after Regione Umbria, 1990).

Historic landslides

The instability of the Rock of Orvieto and of the underlying hill has been known for centuries (MARTINI & MARGOTTINI, 2000). There are fragmentary accounts up to the 13th century: in 1150, following heavy rains, landslides were reported along Ripa di Mezzogiorno, above Corno di Surripa, near the Porta Pertusa (today Porta Romana). Later, Ser Tommaso di Silvestro, in his "Diario" (R.I.S., 1990), describes a landslide which took place near the convent of St. Ludovico. Up until the 17th century another 22 landslides are reported to have occurred on both the Rock and the slopes.

Between 1795 and 1796, following a worsening of the instability, the Castellan of Orvieto ordered that a survey be made to verify the overall stability of the Rock. Documents from the 19th century (REGION OF UMBRIA, 1979) give reports of landslides taking place along the perimeter of the tuffaceous plate, particularly in the area between Porta Rocca and the Fontana del Leone. The largest landslide occurred at the end of the century, near the Convent of St. Chiara. It was described by VINASSA DE REGNY (1904), who attributed the causes of the landslide to the presence of altered tuffs and pozzolana in that area.

In early 1900s, the Porta Cassia landslide, the largest in historical times, took place after a brief period of heavy rainfalls. This was also described by VINASSA DE REGNY (1904, 1905). From the start of the 20th century until the present, falls in the tuffaceous plate and landslides of other types along the slopes have followed each other continuously. The latter have almost always been located at the heads of certain gullies, in particular the Civetta Gully, the Salto del Livio Gully, and the Cavaiene Gully, where the main cause can be attributed to the strong erosion of the basal clays by streams.

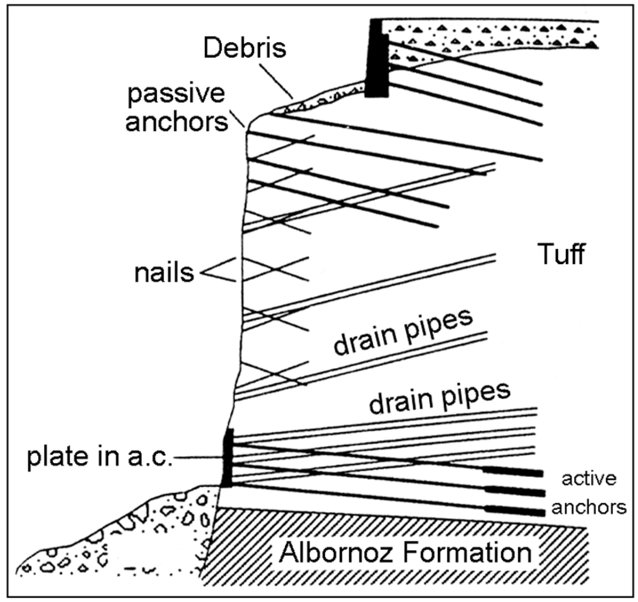

Fig. 9 – Scheme of the strenghtening works along the edge of the Rock (after CONVERSINI et al., 1995).

Stabilization Works

Starting in the late 1970s, following the laws enacted in 1978, 1984 and 1987, a series of works have been planned for the definitive consolidation of the Rock and the stabilization of landslides.

Main works

The main works, which by now are nearing completion, can be summarized as follows (CONVERSINI et al., 1995):

- the water network, including the conduction network and the reservoir, were completely rebuilt. Added to this was the replacement, or at least the renewing, of the entire drainage system, with the building of the relative junction wells and connections to the purifier;
- the gullies originating at the Rock were entirely diked, reshaped, and partially covered, in order to reduce or eliminate the erosion processes taking place, such as the deepening of the bed and the collecting of unstable material at the sides of the valleys;
- the slopes of the hill were reforested, improvements were made to control the flow of water, and all springs were tapped;
- the edge of the Rock was also reshaped, with the building of walls, impermeabilization works, and the planting of greenery;
- works were also carried out to stabilize the landslides along the slopes of the hill, including the building of support structures, trenches, drainage wells and the morphological rearrangement of the slopes;
- the tuffaceous wall was consolidated following a plan adaptable to local needs, taking into due consideration the geometry of the front, its degree of fracturing and the degree of degradation of the wall itself, as well as the environmental value of the site. The plan (FIG. 9) also called for active anchorages at the foot of the Rock (so as to obtain a partial recompression of the tuff) and passive anchorages located on the upper part of the wall, in order to prevent the outermost stone blocks from toppling over. Ample suspension work was also done on the front, bolting down the rock in order to prevent the system of fissures from propagating. At the same time, the cementing of the bolts had as a beneficial side effect also the widespread cementing of the existing fractures;
- the existent city walls standing on the Rock and built in various historical periods were consolidated and restored for preservation (FIGS 10-11), which involved removing plant growth, cementing and cramping loose stones, replacing deteriorated stones, raising the walls, and building underpinnings and buttresses;
- the numerous artificial caves in the tuffaceous Rock were also consolidated, to prevent the roofs from collapsing and the surface from caving in; depending on the historical-archeological importance of the cave, the choice was made whether to simply fill them with mortars of lightened pozzolana mixtures, or to consolidate them with support works, the reinforcing of the walls and cementing, cramping and bracing. Some of these caves are now open to the public and are one of the most interesting tourist attractions.

Figs. 10-11 – The stabilization works on the Rock (photo by P. Marconi).

The monitoring of the works carried out

Subsequently, thanks again to the intervention of the Region of Umbria, monitoring and surveillance systems were set up for the analysis and monitoring of the stabilization and preservative restoration works carried out.

Thus 89 long-base, single and triple extensometers were set up along the perimeter of the Rock to monitor the movements of the tuffaceous plate. The monitoring network consists of 142 sensors set up at 17 measuring stations. Temperature sensors were also connected to the extensometers and placed at various depths in the tuffaceous plate, so as to monitor changes in temperature.

The piezometric levels of the water table were also subject to monitoring, in particular to correlate variations in the piezometric surface level with any landslides occurring.

The network consists of 90 Casagrande-type piezometers located both at the top of the cliff and along the slopes of the hill. About two-thirds of the piezometers are equipped with electric sensors, so as to create a manual/automatic and centralized measurement system. The piezometers were linked to a meteorological data station. Eighty inclinometric tubes were also installed, and 16 of these, placed at the most significant locations, were equipped with centralized automatic reading devices.

The entire system was completed with a series of points for the topographic (planimetric-altimetric) monitoring of the Rock and the slopes, set up both in the intervention areas and in those which have remained stable. The system uses both traditional and GPS measurement techniques.

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