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HYDROGEOLOGY OF THE ISLAND OF SARDINIA (ITALY)

Leader: G. Barrocu

Associate Leader: A. Vernier

Post-Congress **P37**

Field Trip Guide Book - P37

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Front Cover:
Su Gologone spring

Leader: G. Barrocu
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Introduction

The field trip focuses primarily on the hydrogeological aspects of some areas in central-southern Sardinia, taking in the coastal aquifers of the alluvial plains of Capoterra, Cagliari, Muravera and Oristano, and the karsts of Cala Gonone-Dorgali. The route comprises some of the island's most scenic routes, in a succession of cliffs, beaches with wetlands and dunes, and rugged mountains.

In particular the effects of saltwater intrusion due to natural processes and especially human disturbance (river damming and mismanagement) will be considered.

Besides its specific and general hydrogeological interest, the trip will provide an opportunity to appreciate some significant geological, environmental, archaeological and historical features of Sardinia. Sardinia is the second largest island in the Mediterranean (23,833 km^2 or 24,089 km^2 including the small coastal islands), and is mostly mountainous. There is only one large plain, the Campidano, which separates the mountains in the south-west from the rest of the island. Minor lowlands are located around the river mouths on all Sardinia's coasts, especially at its northwestern tip.

The general relief is characterized by massifs, mostly rounded or almost flat-topped, often separated by deep and impenetrable valleys. The highest peak is Punta Lamarmora (1,834 m) in the Gennargentu Mountains in the central eastern part. The average altitude of Sardinia has been calculated at 334 m above sea level.

From a geological and hydrogeological point of view Sardinia may be considered one of the most interesting regions in the world. In its relatively small area, practically all the geological events of the Mediterranean basin are documented, from the Precambrian up to the present day. Almost all of the most well known petrographical types of rocks are represented.

Sardinia has a typical Mediterranean climate, characterized by hot, dry summers and mild rainy winters. Mean annual precipitation is 780 mm, of which less than 11% is distributed in the period June-September. Most of the yearly precipitation falls in the remaining 8 months of the year. Topography affects precipitation significantly, annual rainfall ranging from 1250 mm in the Gennargentu mountains to less than 500 mm on the south-western coast.

Because of its position in the centre of the Mediterranean, Sardinia is practically exposed to all winds, the northwesterly maestrale, being the prevailing wind. Because of intense insolation during the summer, when maximum temperature may reach 42°C, and wind frequency and intensity, actual evaporation is very high, often higher than potential evaporation. The role of hoar frost and dew as supplementary hydrometeors in the hydrologic cycle is still not fully understood.

On the basis of mean temperature and precipitation, Pinna (1954) has established four climatic sub-types of the Mediterranean climate in Sardinia:

1. subtropical with a semiarid variety;
2. warm temperate;
3. sub-humid;
4. humid.

Suspended between Europe and Africa, Sardinia was largely bypassed culturally, and many ancient traditions survive here among its population (1.5 million, with a density of 60 persons/km^2), while only recently has the island been incorporated into the mainstream of modern civilisation.

Regional geologic setting

Geological outline

Practically all the geological events of the Mediterranean basin, from the Pre-Cambrian to the present day, are documented in this relatively small island (24,089 Km^2), with its 1,849.2 km of coastline, a quarter of the total length of Italy's coasts.

Like its neighbouring island Corsica, Sardinia constitutes the remnant of a crustal fragment that has closer geological affinities with some parts of the Iberian Meseta and of Hyeres, Provence, than with Italy.

The crucial period was the Palaeozoic (Figure 1). It was during that long era that Sardinia passed, not unscathed, through two great orogenies: the Caledonian, which affected Cambrian and Silurian sediments, and the Hercynian, which also affected Devonian and Carboniferous deposits. During this era, lithologically-varied sedimentary sequences, attaining a thickness of thousands of meters, were deposited, intruded by granite then partially covered by porphyry flows and finally by magnificent forests of which only traces of fossil flora now remain.

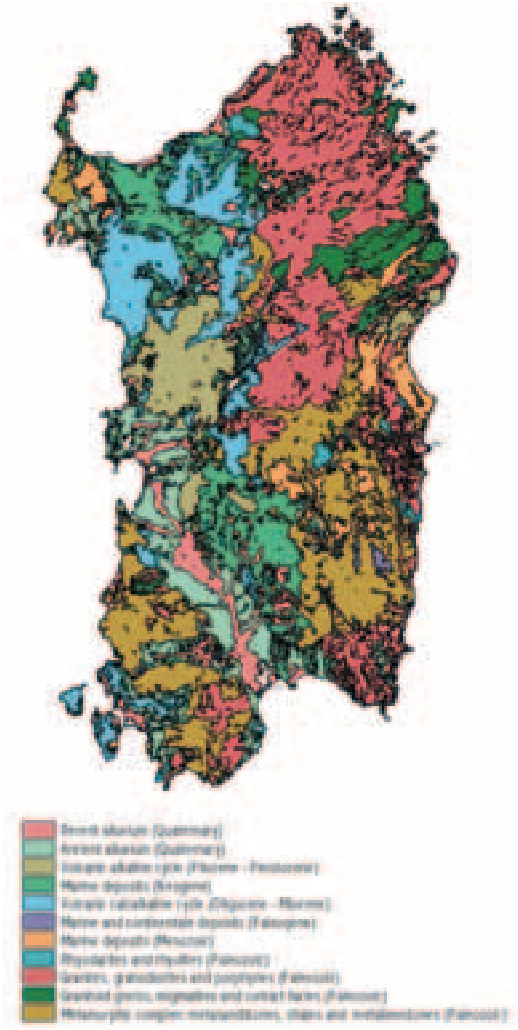

Figure 1 - Geological sketch map of Sardinia.

Sardinia is the only region in Italy where the earliest Cambrian sediments crop out. In Mesozoic times, it was part of a relatively stable platform. After the final phase of the Hercynian orogenic cycle, the island was only affected by isostatic adjustment as a consequence of prior disequilibrium. Contrary to the Palaeozoic, Mesozoic Sardinia behaved as a cratonic area.

Although Sardinia was not submerged completely, the island nevertheless underwent progressive subsidence over areas of varied extent. As the rate of subsidence was very often balanced by sedimentary deposition, the depositional environment varied little over long periods of time, although repeated sedimentary hiatuses occurred.

Sardinia's most recent geological history may be considered a milder repetition of preceding events. In fact, long after the Caledonian and Hercynian orogenic cycles, the island was still affected by minor movements of the Alpine orogenic cycle that deformed the Mesozoic sedimentary rocks, permitting effusions of calc-alkaline magmas and deepening some grabens, such as those of the Campidano and Cixerri. The Mesozoic area preserved its cratonic character, with only vertical oscillations of local portions of the earth's crust so that marine transgression during the Lower Eocene once again covered part of the area, retreating in the Oligocene, to reappear more extensively throughout the Miocene. During the Cenozoic, as in the Mesozoic, it was the western part of the island that underwent the most significant paleogeographical changes. The only sediments remaining in Sardinia from the time are traces of Upper Pleistocene marine deposits along the coast. It is evident that the most recent geological history of this region has evolved quite differently from that of the Italian peninsula.

Tectonics

Transgressions, discordances and sedimentary hiatuses prove to what extent the conditions of the earth's crust and the boundary between earth and sea can change (Figure 2). In some cases the intensity of these phenomena varies in inverse proportion to others. For instance, the greater and longer lasting the transgressions, the fewer the hiatuses. The phenomena of transgression and volcanism indicate the various phases of an orogenic cycle and the geodynamic modifications consequent to it. On the other hand short sedimentary hiatuses correspond to periods of relative orogenic calm. During its long geological history, a region at first clearly orogenic gradually becomes more stable, or cratonic, later experiencing none of the orogenic phenomena of a neighbouring region. This seems to be the case in Sardinia. Here the basement, consisting of pre-Cambrian rocks and Palaeozoic formations from the Cambrian to the Lower Carboniferous, was affected by both the Caledonian and the Hercynian orogenies. The lithostratigraphic units from the Upper Carboniferous-Permian to the present comprise the sedimentary and volcanic cover which has been almost or entirely unaffected by the subsequent Alpine orogenic cycle, even though vast nearby regions have been involved in it.

The overlapping of the effects of repeated orogenies makes it difficult to recognise the gradual changes in geological events necessary to understand the earliest phenomena.

The chronology of the tectonic phenomena may be summarised as follows:

The Caledonian Cycle

Sedimentation in subsiding basins with “external” and “internal” characteristics probably with an intermediate ridge roughly north-northeast of the Campidano graben. This ‘ridge’ presently trends northwest-southeast. Compressive and distensive tectonics were active with an east-west polarity. Initial volcanism was acidic (rhyolitic and rhyodacitic), and subsequently (?) basic (diabase, spilites, etc.). Finally metamorphism was followed by “granitization”.

The Hercynian Cycle

The Hercynian cycle was represented by an intermediate massif between two antithetic orogenies (Variscan to the north and Maghrebian to the south), roughly corresponding to the molassic areas of limited subsidence of the Caledonian cycle. Sedimentation occurred both along and laterally to the dorsal ridge separating the two troughs formed during the previous cycle.

The tectonism was compressive and distensive. Essentially “late” tectonic granites were emplaced at the end of the “molassic” sedimentation. Acidic, (rhyolitic and rhyodacitic) and basic (andesitic) volcanism occurred.

The Alpine Cycle

Triassic-Eocene: The mainly crystalline Palaeozoic basement formed a platform. Local sedimentary Mesozoic covers are varied and discontinuous due to limited local subsidence. Lack of magmatism is apparent.

Oligocene-Quaternary: During the Oligocene-Quaternary the formation of molassic troughs was related to external Alpine troughs. The Oligo-Miocene and Pliocene tectonic cycles evolved independently. The formation of troughs was accompanied by intense, continuous magmatism. There was a lack of compressive tectonics during the entire cycle, but the individual epeirogenic belts of north-south alignment (each with its own evolutionary sequence) may be summarised as follows:

a) The central zone was relatively stable, having been submerged for a short time during part of the Middle and Late Jurassic and possibly in the Early Eocene. This subsidence apparently conformed to transverse alignments which were predetermined by earlier orogenic activity;

Figure 2 - Synthetic structural sketch map of Sardinia basement. 1: Post-Hercynian sediments and volcanites; 2: Granitoids; 3: Very low (south-west Sardinia) to low-grade metamorphites; 4: Main orthogneiss outcrops; 5: Intermediate pressure amphibolite facies metamorphites; 6: Intermediate-pressure amphibolite facies migmatites containing nodules and lenses of rocks bearing relics of granulitic and seldom eclogitic parageneses; 7: Major and minor overthrusts; 8: Hercynian cover; 9: Pre-Hercynian basement (?) (Carmignani et al., 1986).

b) Deposition in the eastern zone diminished from the Dogger to the Tyrrhenian. The eastern zone behaved in a rigid manner and appears to have been affected by the Alpine orogeny as attested to by repeated faults and dislocations, which also extended into the nearby area of the Tyrrhenian Sea;

c) The western zone, apart from the graben areas, was affected in a rather plastic manner by the vertical movements of the crust. These movements were represented by repeated marine transgressions and were responsible for the accumulation of thick continental deposits in the graben which formed during the Alpine orogeny.

Hydrogeology

The geological features of Sardinia are very complex and this is clearly reflected in its hydrogeological structures. Deep and shallow aquifers may be identified, though they are often locally interconnected. Waters infiltrate and circulate at depth along the major tension and shear fractures dissecting the Palaeozoic crystalline bedrock and overlaying formations in upfaulted and downfaulted blocks. Locally, deep hot groundwater issues from springs and wells, but generally their temperature is moderate as in discharge areas hot waters become mixed with cool waters from the upper aquifer levels. Their heat is due either to the geothermic effect associated with their deep circulation or to geothermal anomalies depending on late volcanic phenomena (Barrocu, 2003).

Geophysical investigations with gravimetric, geoelectric, magnetic, electromagnetic, and seismic methods and isotopic studies clearly show that thermal springs in the area correspond to very local phenomena, related to the rise of deep fluids along portions of fault systems or fractured zones within the bedrock complex (Zuppi et al., 2003).

At present, groundwater recharging takes place through the intensive faulting of the rocks throughout the area. Groundwater becomes increasingly heated as it percolates down and is then forced upwards along siphon fractures acting as conduits.

At depth, groundwater becomes heated and is then pushed upwards and also mixed with connate groundwater, likely trapped in unleached fractures and pores of some low permeability bedrock formations as seawater level rose, depending on climate change. In fact, palaeomarine connate waters also control and take part in the steam-rock interaction at depth. Thus, deep fluid circulation is not only peculiar of large sedimentary basins but occurs in cratonic areas as well. Downward movement could be schematically represented as a multi-cell system (Mazor & Nativ, 1994), governed by piston flow. The upward movement is controlled instead by gas pressure and is relatively faster (Zuppi et al., 2003).

The origin of salinity is mainly due to sea level variations during the island's geologic history, especially during the Quaternary. Marine water saturated the impervious rocks and is presently re-mobilized by circulating fluids. Brines, replenishing the most important tectonic contacts, are mobilized at depth by fresh surface waters. Thus, these types of waters reappear on the surface issuing from well known thermal springs, characterized by a high sodium–chloride content, depleted in oxygen-18, tritium free and with a very low carbon-14 activity.

From February to June 1997, a fluid geochemical survey was carried out in Sardinia, taking into consideration physico-chemical and environmental parameters, major elements within gaseous and liquid phases, a few minor and trace elements as well as selected stable isotope ratios (^{2}H, ^{18}O, ^{13}C).

Physico-chemical parameters (temperature, electrical conductivity, pH and Eh), dissolved ^{222}Rn concentration, H_2S concentration (by ORION ion-selective electrode and colorimetric tests) and HCO_3^- concentration (by titration) were determined in the field. The water-dominated hydrothermal areas of the island were considered, all located along regional fault systems: from N to S, the Casteldoria area, the Logudoro area, the Tirso Valley and the Campidano Graben. A number of sites were sampled, including thermal-mineralized, cold springs and wells.

Of course, fresh recent groundwater circulates in the upper fracture zones of the basement, and either issues from a number of springs or is tapped through boreholes a few tens of meters deep, generally less than 100 m. Such aquifers mostly have poor yield and are affected by seasonal rainfall variations.

In the Palaeozoic basement one exception is represented by the large aquifer system of Middle Cambrian limestones in the lead and zinc mining district of Iglesias (southwestern Sardinia). Throughout their long evolution, the limestones were fractured and strongly affected by deep karst (down to several hundred m), in stages depending on the different orogenic phases and sea level variations. Groundwater circuits were disturbed by mining activities in the coastal area, and permeability was strongly increased as shafts and tunnels were excavated down to -200 m. Consequently, the fresh water table was drawn down and sea water encroached on it, to such an extent that a total discharge of 1.75 m^3/s of brackish water needed to be pumped off to enable mining operations to proceed. Only recently, since mining activities have ceased, has the water table increased, and fresh water is now withdrawn, mainly for municipal uses, even if the results are not yet totally satisfactory.

Major aquifers being exploited for municipal use are represented primarily by Mesozoic limestones, and, to a lesser extent, by volcanic formations and alluvial deposits. The effects of over-abstraction are to be observed in coastal areas, almost everywhere affected or jeopardized by saltwater intrusion. On the one hand thousands of wells have been drilled along the coast line, at a distance smaller than the radius of influence of their total drawdown, on the other the surface runoff of major rivers has been dammed upstream so as to meet the increasing water demand. Therefore, floods have drastically diminished downstream and no longer recharge delta aquifers as before. Considering present uses, groundwater resources may be conservatively estimated at 150÷200 hm^3, of which about 50 hm^3 are distributed through aqueducts for domestic water supply. Annual surface runoff averages 6,100 hm^3, of which up to 1640 hm^3 are used in a system of 38 reservoirs to meet major water demand for domestic, agricultural, and industrial purposes.

Field itinerary

DAY 1

Stop 1.1:

Cagliari, the Capital of the Autonomous Region of Sardinia, is situated in the middle of the Golfo degli Angeli (Gulf of Angels), bordering the southern part of the Campidano Graben between the tectonic blocks of the Sulcis, to the west, and Sarrabus, to the south.

The most significant morphologic feature are the ten hills, that though not particularly high (140-60 m), clearly emerge with their trapezoidal profile from the fairly flat zone just a little above sea level. The hills are tectonic blocks composed primarily of sub-horizontal benches of terrain of the transgressive Miocene sandstone-limestone series. The low hillslopes, where the lower arenaceous strata of the series crop out, are for the most part gently sloping, while the largely flat hilltops, composed of benches of calcarenites and biohermal limestones, often have vertical or sheer walls, generally coinciding with fault planes or disused quarry faces. The original morphology has been transformed by human activities, as the hills were quarried for building materials from ancient times up until a few decades ago.

Cagliari (Figure 3), once called Karalis, was founded in the 6th century BC by the Phoenicians, who created a commercial port of call within the S. Gilla lagoon.

The imposing remains of the ancient Punic city's necropolis on the Tuvixeddu hill are now being restored. Occupied by the Romans, the ancient Karalis had its Castrum (castle) in the Marina district, and spread out, above all, onto the plain between the hills and the sea. In addition, in the late Middle Ages, the town, called Santa Igia, was built near the S. Gilla lagoon. Later the Pisans raised a line of defence around the limestone hills dominating the gulf. Only the Pisans were entitled to spend the night in the Castello district. Cagliari, for all Sardinians, became Casteddu. Conquered after a siege by the Aragonese in 1326, it became the capital of the Regnum Sardiniae (Kingdom of Sardinia).

Today the old city lies between the port and the Marina district, with the Stampace district to the west, and the Villanova district to the east, at the foot of the cathedral, the white towers of the central Castello district overlooking them.

The visit starts from Via Roma, in the Marina district, with the imposing Palazzo Comunale (Figure 4) and the parish church of S. Eulalia.

Figure 3 - Map of the historic centre of Cagliari.

In the Stampace district, that was, from the Middle Ages, a residential enclave, are the churches of S. Anna and S. Michele. In the Villanova district, at

Figure 4 - Town hall.

the foot of the Castello, the churches of S. Domenico and S. Giacomo are worth a visit, while looking up from piazza Costituzione one can see the Saint-Remy Bastion.

In the district of Castello, some of the city's most precious architectural monuments can be admired.

The Elephant tower (Figure 5) which dates to 1307, and the tower of S. Pancrazio (1305) built by the Sardinian Giovanni Capula, are among the most beautiful medieval military works in the Mediterranean.

The church of the Purissima is an interesting Catalan gothic monument. In the Piazza Palazzo, which the former royal palace overlooks, is the cathedral of S. Maria, once a significant Pisan building dating from the 1200s, and then extensively modified, which houses numerous works of art. In the newer districts are the Roman Tigellio villa, (1st century AD); the "grotta della Vipera", a beautiful Roman tomb excavated in the limestone rock in honour of Atilia Pomptilia; the Roman amphitheatre (2nd century AD) one of the most important Roman monuments on the island.

Quite close to the district of Castello, in the Piazza Arsenale, the Cittadella dei Musei (the museum complex), with the Art Gallery and the National Archaeological Museum, is worth a visit. The Cittadella was built in 1552 under Spanish rule, but the area has been inhabited since the Phoenician-Punic and Roman ages, as evidenced by two water tanks excavated in the limestone. It was transformed in 1573 for defence purposes and following the artillery's evolution. In 1800 other works were carried out in order to improve the defence system and the Royal Arsenal was built. It was later transformed into a military zone.

In 1943 bombings destroyed the whole structure and it was abandoned. Construction work of the present structure began in 1965 and was completed in 1979.

The National Archaeological Museum houses antiquities dating from pre-historical times to the early Middle Ages.

In particular, finds from the Neolithic and from the Bronze Age can be admired, as well as other important artefacts from the Nuragic Age. Highly suggestive is also the replica of the Tharros "tophet", the emperors Nero's and Trajan's portraits and the black painted pottery.

The Paleo-Christian and Romanesque church of S. Saturno (Figure 6), is a fine example of late medieval architecture of national interest. It re-opened to the public in 1996 after 18 years of restoration.

Figure 5 – Elephant Tower.

To finish, facing the sea, are the sanctuary and basilica of Bonaria (Figure 7), the former built in 1326 in Catalan gothic style, the latter in the 1700s, and finished after the Second World War. It is the most important church on the island.

To the east of Cagliari, the Molentargius lagoon, consisting of two basins with different salinity, is separated from the sea by the Poetto beach, a 15 km long stretch of sand bordering the plain between the hills of the Castello and the highlands of the Sarrabus tectonic block. Its varied wildlife, protected by the Ramsar International Convention, makes the Molentargius lagoon one of the most important wetlands in Europe. Some two hundred species of birds inhabit the lagoon, including pink flamingos. In 1993 a few hundred pairs of flamingos chose a tranquil corner of the lagoon to nest and reproduce, and it has now become their permanent home, under the watchful eyes of tens of thousands of Cagliari's residents. All around the lagoon, really spectacular for its beauty and vastness, all activities such as hunting and fishing are prohibited.

Figure 6 - Church of S. Saturno.

The Poetto beach (Figure 8) is easily reached in a few minutes from the city centre, and lies opposite the Molentargius lagoon, enclosed by the Capo S. Elia. Because of its shape, the summit of this headland is called the devil's saddle, Sella del Diavolo.

The S. Gilla Lagoon, to the West of the city, is a natural area of major environmental interest, separated from the sea by the Giorgino beach, a narrow strip of sand, named after the old Church of Giorgino, and dominated by the Quarta Regia tower.

Figure 7 - Basilica of Bonaria.

Figure 8 - Poetto beach, salt-flats and Molentargius lagoon.

The extensive Santa Gilla lagoon has traditionally provided an endless source of fish for the people of Cagliari. Unfortunately, the surrounding area is today partly altered by road infrastructures, industrial premises and the new container port and canal, and is threatened by pollution. Nevertheless, flamingos continue to inhabit the lagoon, one of their preferred homes.

In the middle of the Gulf of Cagliari, the Poetto and Giorgino beaches are bounded by the promontory of the block of the Sella del Diavolo and Capo S.Elia, from where one can admire the magnificent panorama of the entire gulf. To the west the extreme tip of Capo Carbonara, and Villasimius, to the east the coast of Pula with the ruins of Nora, the ancient Phoenician capital of Sardinia.

Stop 1.2:

From Cagliari to the Natural Monument "Arco dell'Angelo" (50 Km).

General information on the itinerary

The route proceeds along the SS 125 main road climbing up and down winding bends through the characteristic landscape of the Sette Fratelli (Seven Brothers) hills.

Recommended Maps

Topographic maps –IGM tables 1:25,000, series 25: 557 sect. II Quartu S'Elena, 558 sect. III Castiadas and IV Burcei.

Geological maps – Sheet 1:100,000: 234 Cagliari.

The scenic route from Cagliari to Muravera follows the gorges cut by the Rio Picocca and Ollastu in the granite tectonic block of the Sarrabus. The intimate structure of the granite block, crossed by swarms of lamprophyre, aplite, and microgranite dikes, and affected by different systems of precrystalline and postcrystalline tension, shear and overthrust fractures can be observed.

The Sarrabus is an extensive natural area home to a variety of plant species, including Mediterranean bush and conifer stands planted for reforestation of State lands. Along the route the natural arch known as the "Angel Arch" can be seen, classified as a natural monument (L.R.31/89), which was demolished in the mid 1900s to let heavy vehicles through.

The region has a low population density, the main built up areas being Muravera and Castiadas, and can be reached by driving along the picturesque SS 125 main road, through the Sette Fratelli park, a favourite destination for hikers, and the Serpeddì mountains.

Stop 1.3:

From the Arco dell'Angelo to Muravera (30 Km)

General Information on the itinerary

The route proceeds along the same SS 125 main road gradually becoming less winding along the rivers Cannas and Picocca.

Recommended maps

Topographic maps – IGM tables 1: 25,000, series 25: 558 sect. I San Priamo, 549 sect. II Muravera.

Geological maps – Sheet 1:100,000: 227 Muravera, Geological Map of Italy 1:50.000: 549 Muravera.

The Muravera coastal plain, in southeastern Sardinia, was formed by the River Flumendosa, the island's second largest river. The economy of the area relies heavily on agriculture as well as tourism and aquaculture along the coast. The area is also of major environmental interest. As known, in terms of environmental risk, coastal plains are among the most vulnerable areas because of the concurrence of several significant factors. On the one hand, unconsolidated and more-or-less permeable sediments host phreatic and confined aquifers, rivers and lagoons, and maintain the equilibrium between freshwater and the sea. On the other, the coastal plains are attractive in terms of human settlements and related activities such as industry, agriculture, fish farming, tourism, and so on. In this context, the main problems relate to the environmental condition of the aquifers and possible evolutionary trends.

Geology and hydrogeology

As shown in Figure 9, the geology of the delta plain and its surroundings is characterized by a Palaeozoic metamorphic complex cropping out on the edges of the plain, and Pleistocene and Holocene sediments and alluvium, up to a few hundred meters thick, overlying the Palaeozoic bedrock. Granites (Upper Carboniferous- Permian), which are not shown in Figure 9, crop out a few kilometers north of the village of San Vito. Before our geophysical surveys, the thickness of recent alluvium, ancient alluvium, and the metamorphic complex had only been estimated on the basis of morphology and surface geology.

The surface water bodies are the Flumendosa River, its channels at the river mouth, which are no longer connected with the river itself but contain incoming seawater, and several seasonal streams flowing down from the surrounding hills. Apart from the water occurring in the fractured Palaeozoic rocks, from which a few small ephemeral springs issue during the cooler months, groundwater is hosted primarily in the alluvial deposits. To date, the dominant theory is that two aquifers can be distinguished: a shallow phreatic aquifer extending down to a few tens of meters, and an undefined, deeper, confined aquifer, separated from the former by a clay layer, from a few to several tens of meters thick. The lower boundary and deeper stratigraphy of the confined aquifer are still poorly understood by hydrogeologists.

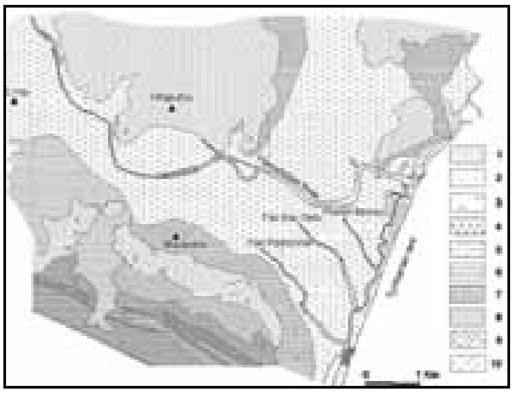

Figure 9 - Geological map of the Muravera plain. Holocene: 1. beach deposits; 2. eolian deposits; 3. recent alluvium; 4. talus. Pleistocene: 5. terraced alluvium. Silurian: 6. carbonaceous shales. Upper Ordovician: 7. metacalcarenites and metalimestones; 8. metasandstones and metaconglomerates. Middle Ordovician: 9. grey and white porphyritic rocks. Middle Cambrian - Lower Ordovician: 10. metasandstones and metasiltstones (Balia et al., 2003).

In the Muravera plain the natural hydrodynamic equilibrium between surface fresh waters and fresh groundwater and seawater is extremely critical. Other than by natural phenomena, such as recurrent drought, this equilibrium has been altered since 1950 by upstream dams and river engineering on the Flumendosa that have diminished natural recharge to the coastal aquifers. The problem is compounded by increasing, uncontrolled exploitation of groundwater for irrigation in the summer. This has resulted in seawater intrusion and progressive groundwater and soil salination, initially observed in the phreatic aquifer.

Groundwater quality monitoring over the past two decades has produced evidence of seawater intrusion (Ardau, 1995). In particular, monitoring of the phreatic aquifer, which began in the ‘80s (Ardau & Barbieri, 1994; Ardau et al., 1996, Barbieri & Barrocu, 1984), indicates progressive saltwater encroachment inland.

In June 1999 we conducted water level and salinity measurements in order to assess groundwater salination (Ardau et al., 2000). The shallow aquifer, (Figure 10) shows electrical conductivity, which is indicative of salinity, of as much as 2000-8000 µS/cm with several peaks of over 20000 µS/cm between the seashore and the town of Muravera. In this regard it should be noted that 2000 µS/cm is the maximum permissible conductivity for many crops, and that the optimum value for drinking water is about 400 µS/cm.

Similar conditions have also been observed in the deep aquifer, as shown in Figure 11.

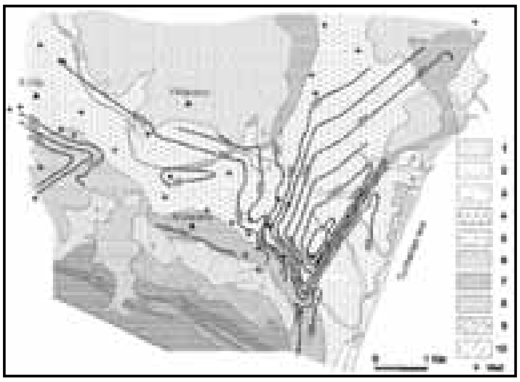

Figure 10 - Water conductivity map of the phreatic aquifer in June 1999. Contour line labels in µS/cm (Balia et al., 2003).

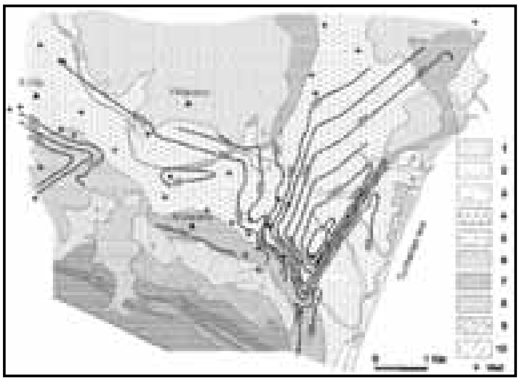

Figure 11 - Water conductivity map of the confined aquifer in June 1999. Contour line labels in µS/cm (Balia et al., 2003).

Main studies (1983-2002)

Studies in the Muravera coastal plain were resumed in 1983-2002, with:
- piezometric, chemical and physical monitoring throughout the network;
- surface water level and quality monitoring;
- exploratory drillings;
- conductivity and temperature well logs;
- vertical electrical soundings;
- gravity surveys;
- reflection seismics.

Recent developments

In order to arrive at an interpretation consistent with the real geological and hydrogeological conditions, we decided to drill several calibration boreholes (Balia et al., 2003). The first borehole (BH1) was located at the first seismic line (SP1), less than a hundred meters away from the centre of VES9 (Figure 12). Our drilling facilities allowed to reach a depth of no more than 35.5 m, since at 32.7 m we came across a harsh gravelly-sandy layer containing high pressure saltwater and were forced to interrupt drilling operations. However, the stratigraphy obtained proved rather meaningful.

In terms of the hydrogeological model and salination status, the results were interpreted as follows. The findings confirmed the phreatic aquifer is separated from the underlying confined aquifer and, also for this reason, they very likely have rather different histories. The phreatic aquifer is actually affected by saltwater intrusion whose present evolution is dependent upon several factors, such as overexploitation, upstream dams, recent artificial channels that have been opened for fish-farming, and recurrent drought. On the

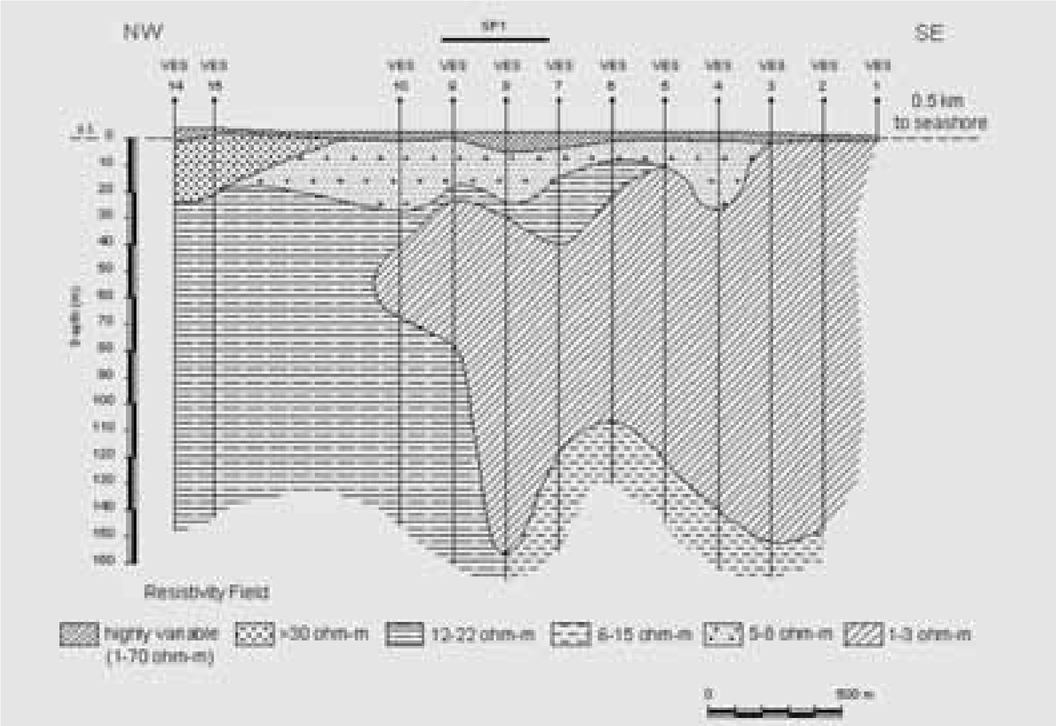

Figure 12 - Resistivity section and seismic profile SP1 locations (Balia et al., 2003).

other hand, salination of the confined aquifer seems to be attributable to quite different causes. It most likely is related to vicissitudes that occurred in the ancient past, when the seashore was situated several kilometres inland from its present position, as attested to by geological studies (e.g. Barca et al., 1981). This interpretation is also supported by two factors: first, that saltwater encroachment is not actually justified in a deep aquifer which has not been heavily exploited until recently, and, second, that recent hydrochemical investigations carried out by Ardau and Barbieri (2000) showed that while the groundwater in the shallow aquifer presents similar characteristics to the seawater, this is not the case of the groundwater contained in the deep aquifer, beneath the clayey layer, which differs significantly from it. This could mean that the saltwater of the confined aquifer does not correspond, or at least not exactly, to present-day seawater.

In order to validate the geological interpretation of the second seismic section previously acquired, and to combine its interpretation with gravity, at least one borehole had to be drilled. This borehole was drilled (BH2) in the middle of the second seismic line (SP2), so as to intercept the main reflectors drilling to a depth of no more than 80-100 m. Again we had to stop drilling at a depth of 42 m, where a layer of a gravelly alluvium cemented by a reddish clayey matrix was encountered. This layer was identified as Pleistocene terraced alluvium, which in itself was very useful information. Thus, in the hope of intercepting the metamorphic basement without interfering with gravelly layers, we moved several hundred meters northwards along the same profile, and drilled another borehole, BH3 (Figure 13).

This reached the metamorphic basement at a depth of 35.6 m. Petrographic analyses on samples confirmed that these metamorphic rocks are fine-grained, siliceous metasandstones and metasiltstones corresponding to unit 10 in the legend of Figure 9.

Finally, from our geophysical results, as well as from boreholes BH2 and BH3, and the surface geology, it was possible to draw the geological section in Figure 13, which is not only qualitative. At least in the southernmost part, where both gravity and seismic information are available, this section contains most of the information considered essential, such as the interface between Holocene and impermeable Pleistocene alluvium, which very likely coincides with the lower boundary of the confined aquifer, the thickness and distribution of Pleistocene alluvium, and the structure and composition of the Paleozoic basement.

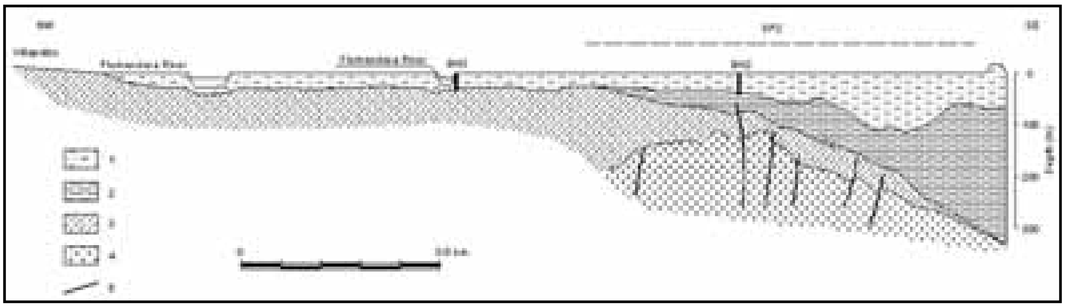

Figure 13 - Quantitative geological section inferred from geophysical data: 1. soil and Holocene deposits; 2. Pleistocene terraced alluvium; 3. Middle Cambrian-Lower Ordovician metasandstones and metasiltstones; 4. Upper Carboniferous-Permian granite; 5. fault (Balia et al., 2003).

Worthy of note are the extensive Foce Flumendosa, San Giovanni, Saline and Colostrai beaches. Beyond the Colostrai beach lies Capo Ferrato, a headland of trachytic rocks. Further south the Costa Rei beach stretches for 8 km (Figure 14), with its holiday homes. Nearby are a number of interesting archaeological sites, in particular the menhir at Piscina Rei and Cuili Piras.

Beyond the River Flumendosa, the tectonic valley that formed on the Villasalto overthrust, creates an anomalous contact between the pre-Hercynian and Silurian-Devonian schist-crystalline series. The E-W trending fault, that crosses the whole Sarrabus region from W to E and likewise the concomitant faults that accompany it northwards, are intersected by minor faults trending on average NW-SE, with small vertical throw and horizontal throw that attains 4 km near San Vito.

Climbing northwards up the Rio di Quirra-San Giorgio tectonic valley, dominated by a block of Silurian limestone, on whose crest rise the ruins of the Medieval Castle of the Marquise of Quirra, ruler of the feudal estate, we proceed up to the Genna Cresia saddle, from which the tectonic valley of the Rio Pardu-Pelau departs, an example of entrapment.

On the summit of the western block, transgressive on the Palaeozoic bedrock, are the peaks of the cover made up of the Jurassic conglomeratic-calcareous-dolomitic series and of the conglomeratic-arenaceous-marly-calcareous-arkosic series of the Eocene M. Cardiga plateau. The limestone and dolomitic limestone strata of the two formations are significantly karstified at depth and form major aquifers.

The Jurassic aquifer, one of the largest in Sardinia, supplies drinking water to a number of towns and villages in central-eastern Sardinia, often situated at the foot of the walls delimiting the formation, along the line of springs in contact with the impermeable schist bedrock.

Stop 1.4:

From Muravera to Lanusei (65 Km).

Figure 14 - Costa Rei.

General Information on the itinerary
The route proceeds along a more-or-less straight stretch of the SS 125 main road.
Recommended maps
Topographic maps –IGM tables 1:25,000, series 25: 549 sect. II Muravera and I Castello di Quirra, 541 sect. II Tertenia and I Jerzu, 531 sect. II Lanusei.
Geological maps – Sheet 1:100,000: 227 Muravera, 219 Lanusei. Geological Map of Italy 1:50.000: 549 Muravera, 541 Jerzu.

The entire Ogliastra region boasts fine white sandy beaches, crystal-clear waters, imposing cliffs that drop sheer into the sea, age-old woods and dry desert plains. Sailing along this magnificent coast, some of the most beautiful bays of the Mediterranean can be admired: Cala Gonone, Cala Luna, Cala Goloritzè, are today all very well-known tourist resorts.
In fact the entire Orosei gulf has been designated an SCI (Site of Community Importance), by the EU for its contribution to conservation of natural habitats and wild flora and fauna.
One of the most well known and popular spots is the Grotta del Bue Marino (sea cow's cave), once home to seals which today are in danger of disappearing.
Numerous species of animals inhabit the area including vultures, birds of prey, moufflons and wild boar, mostly in the interior.
Lanusei, the small capital of Ogliastra is built on the side of a steep hill overlooking a magnificent valley sloping down to the sea. We suggest a visit to the charming cathedral of S. Maria Maddalena, and the domed Temple of S. Giovanni Bosco dominating the urban landscape.
Along the road to Gairo is the Selene forest, where the remains of a Nuragic village are to be found.
Wonderful excursions can be taken up to Monte Sa Ceresia and Punta Tricoli, which offer breathtaking views of the whole Ogliastra region as far as the sea and Monte Ferru at Tertenia. At the top, accessible by a dirt road, one can visit the Astronomic Observatory.

DAY 2

Stop 2.1:

From Lanusei to Santa Maria Navarrese (35 Km).
General Information on the itinerary
The route proceeds along the paved road.
Recommended maps
Topographic maps –IGM tables 1:25,000, series 25: 531 sect. I Tortolì and II Lanusei, 548 sect. III Capo di Monte Santo.
Geological maps – Sheet 1:100,000: 219 Lanusei.

In the charming village of Santa Maria Navarrese with its marina on the Baunei coast, stands a XI Century church of the same name, modified in the 1950s.
Legend has it that the church was built by Isabella, one of the daughters of the King of Navarra, who landed on the coast after being shipwrecked. Near the church are a group of thousand-year-old olive trees, an ancient well and the Tower of Santa Maria Navarrese that dominates the beautiful beach. Built between 1785 and 1790 on a former lookout post of the 1500s, the tower, with its truncated cone shape has a 12-m-diameter base and was originally 10 m high. During restoration work carried out in the mid 1800s another storey was built onto the terrace for use as offices. The original walls, probably in limestone are today plastered with cement.

Stop 2.2:

From Santa Maria Navarrese to coves along the Gulf of Orosei.
General information on the itinerary
The trip, aboard motor boats or large dinghies, starts from the S. Maria di Navarrese marina.

Recommended maps
Topographic maps – IGM 1:25,000 tables , series 25: 548 sect. III Capo di Monte Santo, 547 sect. I Cantoniera Genna Silana, 500 sect. II Dorgali.
Geological maps – Sheet 1:100,000: 219 Lanusei, 208 Dorgali.

From the Santa Maria Navarrese marina, 2.5 nautical miles north of the port of Arbatax on the East coast of Sardinia, the entire coast with its enchanting caves can be visited by boat. The Gulf of Orosei in the centre of which nestles Cala Gonone, is today a marine nature reserve for the protection of the monk seal.
This is the Supramonte, an imposing Jurassic-Cretaceous limestone plateau towering above the sea in the territory of Dorgali and neighbouring villages.
The extraordinary blend of austere rocks and the crystal clear waters of the Tyrrhenian Sea creates myriad natural marvels: to the South Cala Gonone the Bue Marino cave, beyond Cala Fuils which is accessible via a panoramic road, the stony Cala Ziu Martine, with its sheer cliffs and wooded slopes. The Gulf of Orosei is dotted with enchanting beaches -

Cala Luna, Cala Sisine, Cala Biriola, Cala Mariolu, Cala Ispiuligidenìe, Cala Goloritzé (Figure 15) (beneath the 100m high natural pinnacle known as Aguglia) which interrupt the rocky coastline up to Capo di Monte Santu.

The coastline forms the seaward boundary of the Baunei Supramonte and also delimits the area designated to become the National Gennargentu Park.

Stop 2.3:

From the coves of the Gulf of Orosei to Cala Gonone. General information on the itinerary

The route continues by boat or large dinghy to the Cala Gonone marina.

Recommended maps

Topographic maps – IGM 1:25,000 tables, series 25: 548 sect. III Capo di Monte Santo, 547 sect. I Cantoniera Genna Silana, 500 sect. II Dorgali.

Geological maps – Sheet 1: 100,000: 219 Lanusei, 208 Dorgali.

Cala Gonone is renowned above all for its fascinating boat trips. A very well-organized boat service, which first started in 1954 when the Bue Marino caves were opened to the public, ferries tourists the 4 km along the coast from the harbour to the caves a little further on from Cala Fuili. The caves are visited by tens of thousands of tourists each year.

Beyond the impressive entrance, recognizable by its gigantic column, the cave divides up into a fossil part (north branch) and an active part (south branch), where the seawater mixes with the freshwater spilling from the innermost parts of mountain. This part, now lighted and opened to the public in 1983, is studded with concretions, stalactites and stalagmites that reflect in the crystal clear pools. The tour finally brings us to a large cavern in the middle of which is a stalactite column and, at the back, a wide beach (known as the seals' beach) where, up to the 1960s, the rare pinnipeds used to seek shelter to give birth to their young and to rest. No words can describe the spectacular secrets of this fascinating underworld.

Seven kilometres from Cala Gonone marine 3 km South of the Bue Marino cave, is Cala Luna, a paradise not to be missed by tourists travelling to the Barbagia region. In the summer a boat service runs regularly between this beach, and also to Cala Sisine, and Cala Gonone (refreshment kiosk on the beach). Cala Luna has been described as the Mediterranean's most beautiful beach. Six huge caves open out onto it and the coastal lagoon is fringed by oleanders. At the southern end Punta Su Masongiu (115 m), a high wooded rocky cliff that shelters the crescent moon bay from scirocco (warm, southerly) winds.

Figure 15 - Cala Goloritzé.

Equally attractive is the coast north of Cala Gonone. The stretch of coast between Cala Luna and Pedra Longa has been designated a protected area for the safeguard of the monk seal and access to and navigation in this part of the coast is restricted.

DAY 3

Stop 3.1

From Cala Gonone to the Genna Silana Pass
(37 km).

General information on the itinerary

The main route proceeds along the paved road. Having reached the Genna Silana pass (1008 m) the route continues along an unmade-up road, which can be easily followed on foot or in an off-road vehicle. There are wonderful excursions into the Dorgali Supramonte and to the Gorroppu canyon a spectacular gorge cut in the limestone rocks by the waters of the Rio Flumineddu.

Recommended maps

Topographic maps –IGM 1:25,000 tables, series 25: 547 sect. I Cantoniera Genna Silana, 500 sect. II Dorgali.

Geological maps – Sheet 1:100,000: 208 Dorgali.

The "Orgosolo-Oliena-Urzulei" Supramonte is one of the largest karstified massifs in Sardinia.

It extends over about 170 km^2 and supplies the Su Gologone, San Pantaleo and Su Tippari springs, situated along the right bank of the River Cedrino in the Oliena and Dorgali countryside, as well as the Gorropu spring that gushes from the central-eastern slopes of the Supramonte.

From a geological and hydrogeological standpoint, the Supramonte is composed primarily of dolomitic limestone rocks, of the Jurassic-Cretaceous sedimentary succession that crop out in most of Central-Eastern Sardinia (the carbonate massif along the Gulf of Orosei coast, Monte Albo and Monte Tuttavista).

This sedimentary succession rests with stratigraphic and angular discordance on the schist and/or granite terrains of the Palaeozoic crystalline basement that only crop out extensively in the southernmost portion of the Supramonte. It is composed of polydeformed schist-like sediments petrographically determined as belonging to the green schist facies of the biotite zone.

The structural setting of the Supramonte, variously interpreted in the past, has recently been re-examined by Pasci (1997), who relates the geological evolution of this area with the transpressive tectonics of the Alpine age believed to have affected various parts of the crystalline basement and pre-Alpine sedimentary successions.

On the other hand, the overall hydrostructural and hydrogeological setting of the Supramonte has been determined, through detailed studies of the area, and by monitoring springs and field surveys, by Sanna & Vernier 1993; Sanna (1996) and Sanna et al. (2002), and on the basis of the findings from karst cavity exploration and groundwater tracing conducted by various groups of speleologists. These include La Federazione Speleologica Sarda, Gruppo Grotte Nuorese, Centro Speleologico Cagliaritano, Gruppo Grotte Cagliari, Gruppo Archeo Speleo Ambientale Urzulei, Gruppo Ricerche Ambientali Dorgali, Speleo Club Oliena, Gruppo Speleo Archeologico Giovanni Spano Cagliari, Unione Speleologica Bolognese and the Gruppo Speleologico Faentino which have provided an important contribution to gaining a better understanding of the hydrogeology of the area.

Research conducted by the above authors have enabled the Supramonte groundwater flow pattern to be determined, using the basic conceptual model proposed by Civita et al. (1992) for more or less fractured and karstified carbonate aquifers to interpret groundwater circulation.

The findings of their work also suggest that the central-northern part of the Supramonte hosts an aquifer that may potentially contain major and strategic groundwater resources. A better understanding and quantification of this resource would enable to increase drinking water supplies in the area, which are presently secured by partially capturing groundwater from the smaller Su Gologone spring.

No new data are provided here for gaining a deeper insight into the hydrogeology of the Supramonte, but the information gathered to date is summarized using the graphic schemes published by Sanna et al. (2002).

General information concerning the hydrostructural and hydrogeological setting of the Supramonte

From a strictly hydrogeological point of view, Sanna & Vernier (1993), identified five main sectors in the Supramonte (Figure 16). These were identified on the basis of the bedding relationships between the carbonate cover, the underlying Palaeozoic basement and on the horizontal and vertical orientation of the contact surface between the two formations.

The contact between the crystalline basement and the overlying carbonate rocks in the first sector (Figure 16, sections A, B and C), between Oliena and the Rio Flumineddu valley, situated to the north of Monte Omene, first occurs at an altitude ranging from 800

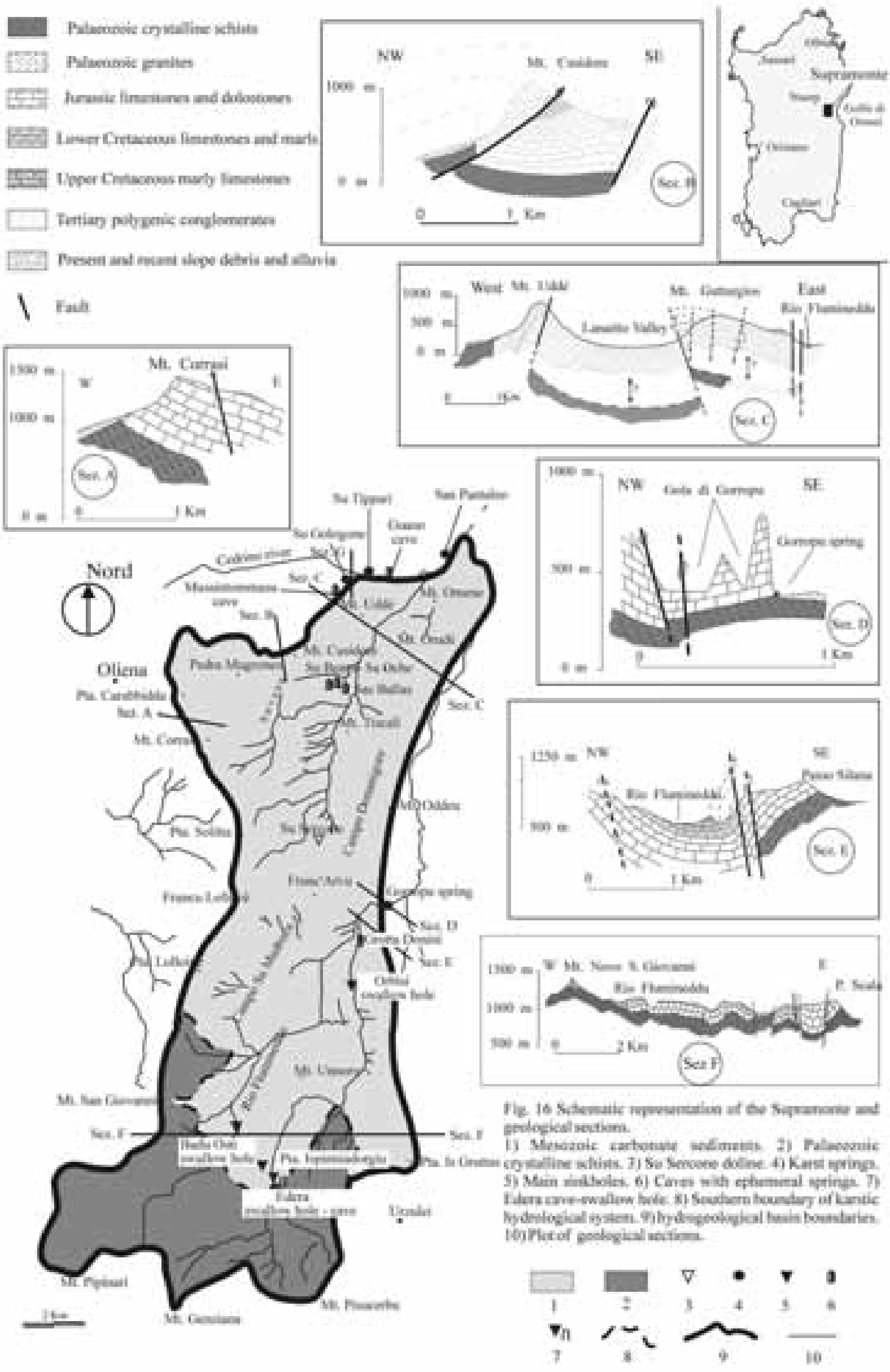

Fig. 16 Schematic representation of the Supramonte and geological sections.
1) Mesozoic carbonate sediments. 2) Palaeozoic crystalline schists. 3) Su Sercone doline. 4) Karst springs. 5) Main sinkholes. 6) Caves with ephemeral springs. 7) Edera cave-swallow hole. 8) Southern boundary of karstic hydrological system. 9) hydrogeological basin boundaries. 10) Plot of geological sections.

to 900 m a.s.l., descending to around 100 m a.s.l. in the area between the Su Gologone and San Pantaleo springs.

The basement–cover contact in the second sector (Figure 16, sections C and D), on the eastern edge of the Supramonte, is tectonic in nature and lies at between 100 and 350 m a.s.l. near the Gorropu spring.

In the third sector (Figure 16, sections D and E), between the Gorropu canyon and the Genna Silana pass, the basement–cover contact is directed westwards, rising gradually from 350 m a.s.l. to 1000 m a.s.l. near the pass.

Along the southern edge (Urzulei Supramonte) and the western fringe of the carbonate massif (Figure 16, sections A and F), the fourth and fifth sectors respectively, the Palaeozoic bedrock is overlain by the Mesozoic sedimentary cover. The boundary, lying at an elevation of at least 800 m a.s.l., is often obscured by Quaternary detritus sediments.

The limestone sequence shows clear signs of deformation, notably major transpressive faults (Pasci, 1997), like the ones at Lanaitto, and folding of the Mesozoic sediments. The most conspicuous folds are the Gorropu and Lanaitto synclines where Cretaceous beds occur towards the core.

On the whole, it exhibits S-N verging, the aquifer being totally confined by the impermeable schist-granite formations of Palaeozoic age.

Springs and hydrogeological setting of the northern Supramonte

The Supramonte’s main karst features have formed along the northern edge of the limestone formation where the Su Gologone spring, a small pool of water not marked on official maps but whose hydrogeological significance was recognized by Sanna et al. (2002), comes out and, further down the valley, the Su Tippari and San Pantaleo springs emerge.

At Su Gologone (elevation about 103 m a.s.l.) groundwater emerges as two springs called “Sa Vena Manna” and “Sa Vena Minore”.

Because of the stunning landscape in which the springs are set Su Gologone has been officially recognized by regional authorities as a natural monument.

From a hydrostructural standpoint, the springs can be classified as having emerged due to juxtaposition of the permeability threshold. According to Sanna & Vernier (1993) the emergence of groundwater (Figure 17) may likely be attributed to the existence of a permeability threshold that was produced when the contact between the crystalline bedrock and Mesozoic carbonate cover was upturned and partially overturned in the entire sector between the area upgradient from Su Gologone and the San Pantaleo springs.

The Sa Vena Manna spring can also be described as a typical vauclusian spring as the groundwater rises up a karst conduit that has been explored down to a depth of around 107 m and is very likely the upper end of a large siphon.

Groundwater from the Sa Vena Minore spring gushes from a fracture in the rock which is connected to the main karst network. Part of the spring water is captured, average withdrawals amounting to some 100 l/s.

A comprehensive study conducted for assessing water resources in the Supramonte, included monitoring of the Su Gologone springs. Based on the results it has been possible to reconstruct spring flow from the main spring, which was found to range from 60 l/s during dry periods to a flood flow rate of 8000 l/s.

Comparison of fluctuations in water level with rainfall regime in the Supramonte showed flow in the monitored spring to behave rather impetuously.

In fact, sharp increases in spring flow were always observed even after not particularly heavy rainfall, with lag times ranging from a few to 24 hours (time interval for water level measurement) from the onset of precipitation, Sanna et al. (2002). Similarly, once rainfall had ceased, and in the absence of further infiltration episodes, flow rate was found to decrease rapidly and resumed initial values relatively quickly

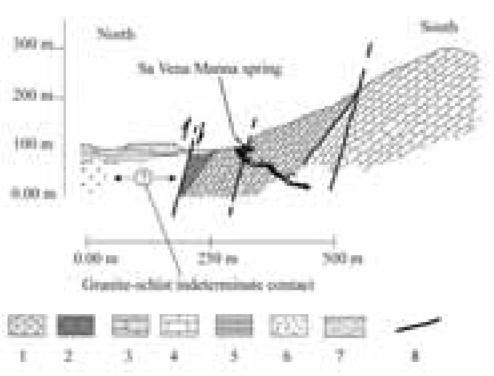

Figure 17 - Schematic geologic cross-section of main “Su Gologone” spring: 1) granite; 2) schist; 3) basal Jurassic dolostone; 4) Jurassic limestone; 5) ancient terraced alluvia; 6) Plio-Pleistocene fluvial-lacustrine deposits; 7) Recent and present alluvial sediments.

except for major recharge events when lag times of as much as 30 days were recorded.

Unfortunately, access to the other springs in the Supramonte, situated further downvalley, is impeded for most of the year as they are submerged beneath the Cedrino reservoir.

For this reason it proved impossible to monitor flow rates, as had been done for Su Gologone.

However, the scant data reported in the literature indicate the San Pantaleo springs to be situated at an elevation of around 95 m a.s.l. and to have flow rates comparable with the Su Gologone springs. On the other hand the Su Tippari spring lies at an elevation of around 100 m a.s.l. with an estimated minimum flow rate of roughly 25 l/s.

Two large karst cavities have been identified along the northern edge of the carbonate massif. The first, the Guano cave, is situated between the Su Tippari and San Pantaleo springs, the second the Mussintommasu cave (also known as Peppino Ladu cave) lies a little further uphill from Su Gologone.

Both these caves only become flooded after major infiltration events when they act as overflow springs.

The Guano cave, which has three entrances at elevations of between 95 and 120 m a.s.l., consists of a spacious tunnel, reaching a maximum elevation of 107 m a.s.l. The cave extends for approximately 2 km underground and has two sumps located at an elevation very close to the Su Gologone springs.

The entrance to the Mussintommasu cave lies at an elevation of about 118 m a.s.l. in a rocky wall above Su Gologone and extends over no more than 50 m. This karst cavity is of major hydrogeological interest because at 103 m a.s.l., which coincides with the outlet elevation of the Su Gologone springs, it is permanently filled with water. Pot-holers and underwater exploration have reached a depth of roughly 80 m from the surface.

To the South of the springs, proceeding into the heart of the Supramonte, are another two large cavities: the Su Bentu-Sa Oche complex and S'Istampu Sas Ballas.

These caves form part of a single karst system of which to date 16 km have been explored. The system consists of spacious cave passages that were later deepened by running water. The caves become partly flooded after heavy rainfall. After exceptional rainfall events the Sa Oche and Sas Ballas, and similarly the Guano and Mussintommasu cave mouths, act as overflow springs yielding flow rates of up to several cubic metres a second.

The Su Bentu-Sa Oche complex has two separate entrances. The opening to the semi-active cave (Sa Oche) lies at an elevation of around 150 m a.s.l., that of the inactive portion (Su Bentu) at about 200 m a.s.l.

The entrance to the Sa Oche cave leads into a wide passage that ends abruptly after just 200 m, at an elevation of 135 m a.s.l., in a sump which is connected to the semi-active passages of the Su Bentu cave.

The Su Bentu cave consists of a vast system of water carved passages extending over a total length of more than 14 km. In several places the passages reach the saturated zone, situated at an elevation of approximately 105 m a.s.l., thus very close to the main groundwater emergence at Su Gologone.

The S'Istampu-Sas Ballas cave, whose entrance lies at 143 m a.s.l., extends for about 2 km and at 117 m a.s.l., a short distance from the rear end of the cave, reaches a siphon.

Several areas of both the Sas Ballas and Su Bentu–Sa Oche caves are partly flooded even at elevations way beyond the saturated zone. A number of underground lakes have formed in these areas that based on information collected to date can be interpreted as "perched" zones of the karst system.

Hydrogeological features of the southern Supramonte

The southern portion of the Supramonte forms the main source of groundwater supply to the karst system drained by the Su Gologone springs.

Here, several swallow holes or stretches with losses beneath the streambed have formed close to the bedrock-carbonate cover contact. There are also a few caves that function as water collectors conveying groundwater towards the deeper parts of the karst aquifer.

The Badu Osti swallow hole, situated at an elevation of 892 m a.s.l. and the most important groundwater loss point receives discharge from the upper Rio Flumineddu.

The most interesting karst cavity in hydrogeological terms is the Edera system, the entrance to which lies at approximately 950 m a.s.l.

Inside this cave is a main collector structure that hosts a subterranean torrent with variable flow rate. After following a relatively winding path through the passage, the water of this torrent is dispersed in an area of the cave that as yet remains unexplored.

Two water tracing tests have been carried out at the Badu Osti swallow hole and the Edera cave. The first, conducted in August 1969 by the Gruppo Speleologico Faentino, the Unione Speleologica Bolognese and the

Centro Speleologico Cagliaritano, indicated that the waters captured by the swallow hole at Badu Osti flow into the main collector in the Edera cave at a point situated at an elevation of approximately 738 m a.s.l. (Assorgia et al., 1968).

The second test was carried out by the Federazione Speleologica Sarda (Sardinian Speleological Society) in June 1999. The water tracer was introduced into the Edera cave downstream from the point where the torrent joins the water flowing in from the Badu Osti swallow hole, i.e. where no speleological exploration has been possible.

10 Kg of Na-fluorescein tracer was used for this test, with satisfactory results, recorded 76 days later at the Su Gologone and Su Tippari springs, Bandiera F. et al. (2002).

The main karst hydrological system in the Urzulei Supramonte also hosts a number of secondary sub-systems, the most important being the Orbisi–Donini cave.

Following heavy rainfall, this karst cavity receives part of the surface runoff collected in the groundwater catchment basin in the Palaeozoic bedrock of the southern Supramonte. During flood flow the water discharged from this zone is partly absorbed by the Edera system, while the excess flow is conveyed along the Codula Sa Mela, eventually ending up in the Orbisi swallow-hole at an elevation of approximately 790 m a.s.l. This swallow-hole is connected to the Donini cave. From the cave opening in a vertical wall further downvalley, gushes the groundwater captured in the Orbisi swallow-hole, continuing its journey above ground, eventually joining the Rio Flumineddu below.

The surface water is then captured by a series of small sinkholes beneath the Rio Flumineddu and returned to the underground karst network.

Lastly, SE of the Orbisi-Donini cave, and much further downslope, at an elevation of approximately 350 m a.s.l., lies the Gorropu spring.

This spring emerges close to the stratigraphic contact between the basement and the carbonate aquifer and is characterized by a very variable hydrodynamic regime, discharge flow rates ranging from more than 1000 l/s to no more than 10 l/s in dry period.

How the karst system works

The results of research carried out in the Supramonte and in particular the water tracing tests performed in 1999 by the Federazione Speleologica Sarda in the Edera cave, have unequivocally confirmed that the carbonate massif forms a single hydrological system. It is the southern sector of the Supramonte that supplies the karst network. In fact, not only are there several points in this part of the massif where surface runoff infiltrates through the surface, but several caves and waterpools also exist from where the groundwater flows rapidly towards the springs situated in the northernmost part of the Supramonte.

Speleological observations, monitoring of the Su Gologone springs together with the hydrogeological and hydrostructural surveys indicate the presence of a relatively extensive saturated zone in the karst network in the central-northern part of the Supramonte.

On the surface this zone coincides with the area between the northern part of the Supramonte where the springs emerge (Su Gologone, Su Tippari, San Pantaleo), the Lanaitto valley and the central part of the massif where the bedrock-carbonate cover contact can reasonably presumed to be situated below the local base level of between 103 m a.s.l. and 95 m a.s.l. (Su Gologone and San Pantaleo).

The existence of a saturated zone in the karst system to the south of the area where the springs emerge, justifies the rapid response of the Su Gologone springs observed by Sanna et al. (2002) during monitoring of the larger spring.

Clearly the abrupt increases in water level observed, which almost always coincide with rainfall events, indicate the existence of a drowned aquifer, with high pressure karst conduits situated beneath the level of the Su Gologone spring. Any perturbations in the system, like those caused by major infiltration episodes, increases the pressure in the conduits which is accompanied by increased flow rate at the point of groundwater resurgence.

Large amounts of infiltrating water or infiltration that occurs in limiting conditions, when for example the aquifer has already been partially recharged, can increase water levels and flood the caves situated at increasingly higher elevations compared to the local base level of the Su Gologone, Su Tippari e San Pantaleo springs.

It is worth mentioning that speleological and hydrogeological observations have shown that floodwaters in the karst system reach the Su Gologone springs in a relatively short time. Longer lag times have been recorded for the Guano e Mussintommasu caves, while it takes a few days before the gradual increase in water levels makes the springs gush from the Sa Oche e Sas Ballas cave entrances.

The above findings indicate that in hydrogeological terms all the caves existing in the northern part of the (Guano, Mussintommasu, Su Bentu-Sa Oche and Sas

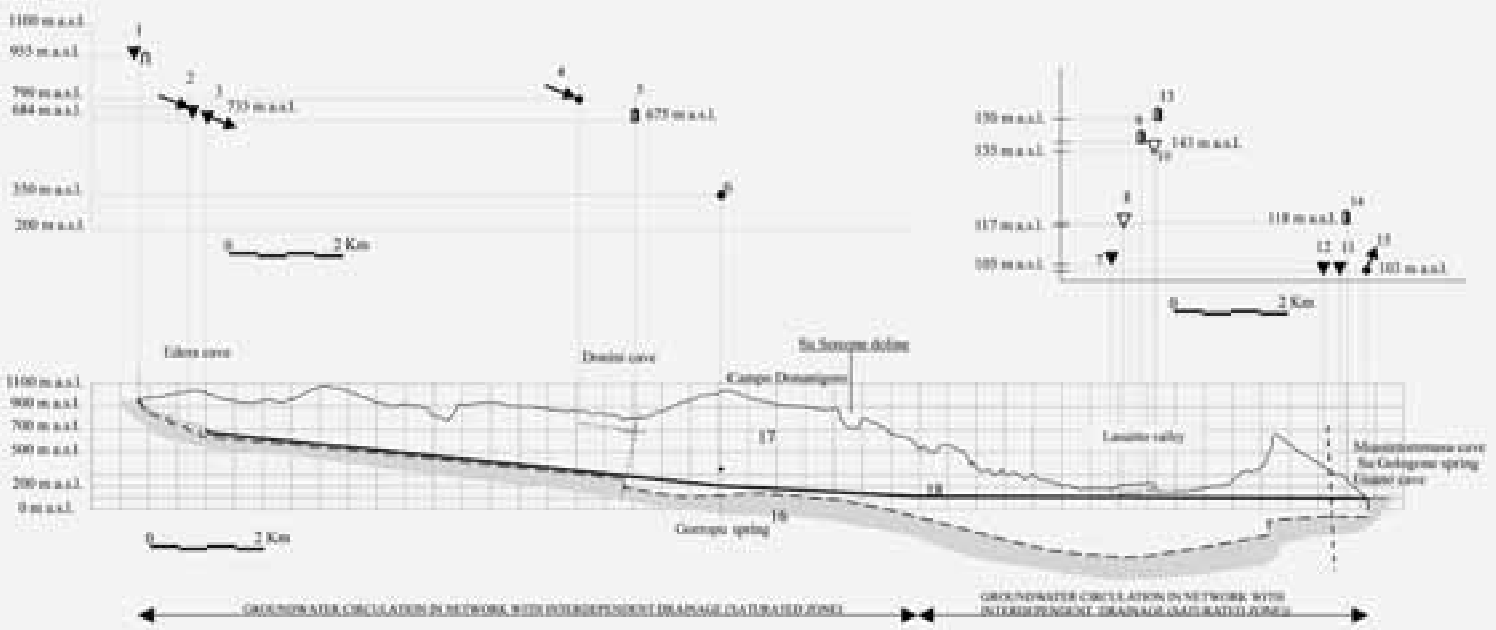

Fig. 18 - Schematic profile of the Supramonte from the Edera cave to the Su Gologone spring. It schematises how the karst system works in relation to the possible bedrock topography underlying the Supramonte karstic hydrological system and to the elevation of the examined sinkholes, karst systems and spring outlets. It shows the hydrogeological role of each system: the Lanaitto caves form a semi-dependent sub-system with the basal saturated karst acting as overflow springs the Donini cave forms a secondary suspended system that contributes directly supplying the waters draining from the Gorropu spring the Edera cave receives the water coming from the crystalline bedrock that infiltrates through the Badu Osti sinkholes (to the East) and other sinkholes situated near the cave entrance. The Edera cave is thus the most important system known so far with dominant primary circulation and supplies directly the basal saturated karst situated in the northern Supramonte and drained by the Cedrino springs.

To get a clearer picture of the elevation of the spring outlets, the water levels of the saturated karst system, of the suspended system and of the dominant primary system with a graphical scheme, the longitudinal profile where the elevation scale is much more stretched than the horizontal distances is given above.

Symbols used 1) Entrance to the Edera Cave 2) Point where water coming from Badu Osti sinkhole flows into the Edera cave. 3) Losing point of water in the terminal rockfall of the Edera cave 4) Orbisi swallow hole 5) northern entrance to the Donini cave 6) Gorropu spring 7-11-12) Elevation of basal saturated system measured at terminal sumps in Su Bentu, Guano and Mussintommasu caves, 8-10) Elevation of suspended sumps in the Sas Ballas and Sa Oche caves, semi-dependent with the basal system; 9-11-14) entrance to the Sas Ballas, Sa Oche, Mussintommasu caves; 15) Su Gologone spring (which practically coincides, in projection, with the lower entrance to the Guano cave); 16) Crystalline bedrock; 17) Mesozoic carbonate rocks; 18) water level contour line

Ballas) act as overflow springs.

To better characterize the karst aquifer in relation to other aquifers in Italy, Sanna et al. (2002) have schematically described the karst network of the Supramonte using the basic conceptual modelling technique proposed by Civita et al. (1992).

In this sense, in the subterranean passages and cavities of the Supramonte there is a primary dominant groundwater network (Urzulei Supramonte –Edera system), as well as an "interdependently draining" network (central-northern Supramonte).

In the southern part of the Supramonte a strong hierarchy of the drainage network exists, numerous collectors within large karst conduits rapidly draining even large quantities of inflowing water, as happens inside the Edera cave.

In this case groundwater circulation is governed to a large extent by bedrock topography, the system's reserves are scant and the flow rates vary significantly depending on the amount of water infiltrating into the groundwater network.

On the other hand, in the central-northern part of the Supramonte exists a saturated zone with a network of variously connected conduits and fractures that host major groundwater reserves.

In this case, as speleological observations have demonstrated, the water levels in the system vary significantly. This is both because a level exists beneath which the cavities are perennially flooded, and because an upper fringe occurs where perched zones arise and within which groundwater only flows when the Su Gologone, Su Tippari and San Pantaleo springs are unable to cope with the huge quantities of inflowing water infiltrating through the carbonate massif.

Figure 18 shows a longitudinal section of the Supramonte. It illustrates the groundwater circulation pattern described above in relation to the elevation of the karst systems and perennial springs, and to the presumed water level of the basal saturated karst.

One very interesting excursion is to the heart of the Dorgali countryside, proceeding south along the SS 125 main road, past the tunnel for Cala Gonone and stopping at the Genna Silana pass.

Figure 19 - Su Gorroppu.

This route takes in the entire eastern edge of the carbonate massif, the Gorropu spring and the main geomorphological features of the area. The contact between the crystalline bedrock and the Mesozoic carbonate cover is clearly visible as well as the entrance to the Edera cave and a number of points where surface runoff infiltrates through the carbonate structure flowing into the karst network.

The Gorroppu canyon is a spectacular karst gorge approximately a million years old. Its vertical walls are more than 400 metres high.

Visitors have plenty of time to visit an interesting part of the canyon (Figure 19).

Scattered about the Gorroppu gorge, which is situated in the territory of Urzulei, are enormous rounded rock masses. Birds of prey nest in the crevices of its dizzyingly high walls. Only experienced mountaineers can attempt to climb up the sheer walls, which at a certain point are interrupted by perennial lakes.

Stop 3.2:

From the Genna Silana Pass to Su Gologone (60 km).

General information on the itinerary

The route follows the paved road to the famous Su Gologone restaurant. The short path leads us alongside the rocky wall, amidst eucalyptus woods near the River Cedrino and thick Mediterranean bush.

Recommended maps

Topographic maps –IGM Tables 1:25,000, series 25: 500 sect. II Dorgali, III Oliena.

Geological maps – Sheet 1:100,000: 208 Dorgali.

On reaching the Su Gologone spring- Mussintommasu cave (Figure 20), you will also be able to see the sub-vertical contact between the basement and carbonate cover which is partly overturned.

The karst Su Gologone spring is an important and fascinating spring. All year round its waters feed the Cedrino reservoir which supplies water to towns and villages in the area. Its fascination lies in its undiscovered mysteries. Several attempts have been made to explore the innermost core of these springs. The current record is held by the Frenchman Olivier Isler, one of the famous cave-divers sponsored by "Sector", who succeeded in descending to 108 metres, but without reaching the bottom.

Stop 3.3:

From Su Gologone to the Lanaitto Valley (10 km).

General information on the itinerary

To reach the valley (Figure 21), turn right before the large square where the springs are situated. The road, marked with a sign, is cemented for the first few kilometres but then turns into a dirt road. Follow this track, preferably by jeep for about 8 km until you come to a cross-roads. To the right, the Sa Sedda e Sos Carros nuragic village, to the left the Nuragic village of Tiscali. Turn left and continue for a few kilometres until you come to the valley.

Recommended maps

Topographic maps – IGM Tables 1:25,000, series 25: 500 sect. III Oliena.

Geological maps – Sheet 1:100,000: 208 Dorgali.

Figure 20 - Su Gologone spring.

Once you have reached Lanaitto Valley you will be able to admire the synclinal structure bounded by two lateral transcurrent faults and the boundary between the carbonate structure and the Palaeozoic bedrock.

Lanaitto Valley is the paleovalley of the River Flumineddu. Following landslides and earthquakes in ancient times today the river flows much further eastwards in the Dorgali territory.

The river flowing through the Lanaittu valley, called the Rio Sa Oche, is one of the numerous torrents that over the millennia have carved out the extraordinary karst landscape of the Supramonte, including the famous Sa Oche, Su Bentu and Eliches Artos caves. Alongside these surface erosion processes have created an endless series of narrow gorges, crevices, dolines, gaping sinkholes and rock crags creating a striking and distinctive landscape.

Lanaitto Valley is one of the areas in the Supramonte with the largest number of cavities, chasms and caves carved into the limestone ridges of this heterogeneous and tormented complex. They bear witness to the eroding force of impetuous rivers long since disappeared that in ancient times shaped the entire region. These include the Corbeddu cave, named after a famous bandit who took shelter there in times

Figure 21 - Lanaitto valley.

gone by. This cave is of significant archaeological and paleontological interest for the large hoard of finds discovered and the rare species of insects identified (Bathysciola majori, Patriziocampa sardoa). However, the cave became famous after the discovery, by an expedition of American scientists and the Gruppo Grotte di Nuoro, of the first complete skeleton of the Prolagus sardous, an ancient rodent that became extinct about 4,000 years ago for reasons unknown.

Stop 3.4:
From Lanaitto valley to the Su Bentu and Sa Oche caves.

General information on the itinerary

Proceed in the same direction as the previous stop until you reach, at a short distance from the archaeological site, the complex groundwater system of the Sa Oche (the voice) and Su Bentu (the wind) caves.

Recommended maps

Topographic maps – IGM Tables 1:25,000, series 25: 500 sect. III Oliena.
Geological maps – Sheet 1:100,000: 208 Dorgali.

Take a look at the cave entrances and examine the relationships between the elevations of the discharge points of the main springs at Su Gologone, Su Tippari e San Pantaleo.

The “Sa Oche-Su Bentu” system is one of the longest (over 20 km) and most interesting caves in the Supramonte. Newcomers might well find the route rather challenging with its succession of rooms separated by slight ascents and descents that eventually lead to the first pools. But they will find it was well worth the effort and will be stunned by their breathtaking beauty and crystal clear waters. Usually visitors turn back once they have visited the first pools. To visit the whole cave system takes at least 20 hours and of course requires some degree of experience.

Stop 3.5:
From the Su Bentu and Sa Oche caves to Monte Tiscali.

General information on the itinerary

The route to the Tiscali Nuragic village takes us through a crevice that splits the huge, magnificent mountainside to the North. It is a one-and-a-half-hour trek to the village, sometimes across difficult terrain.

Recommended maps

Topographic maps – IGM Tables 1:25,000, series 25: 500 sect. III Oliena.
Geological maps – Sheet 1:100,000: 208 Dorgali.

On the south-eastern edge of the Dorgali-Oliena Supramonte lies the Tiscali doline, on the crest of the craggy Monte Tiscali, which marks the boundary, together with the Lainatto valley, between the two territories. The route crosses the so-called Curtigia di Tiscali, a crevice in the mountainside that was most likely created by the same geological process that a few million years ago produced the large doline a little further up the mountainside. Several hollows, carved by wind/water erosion, fissures and gulleys appear in the rocky mountain sides, which are covered in places with thick vegetation and enormous holm oak and juniper trees. Once we have climbed up the

Figure 22 - Nuragic hut.

steep stony scree, and through the crevice, the route proceeds for a long stretch along the inside of a niche, a bright reddish wall looming tall above. Finally we reach the single entrance to the doline, a gigantic limestone cavity created by tectonic movements. Scattered over the bottom of the cavity are the remains of what was once a large Nuragic village, dating to the latter part of the Nuragic age.

The forty or so largely round, but some rectangular, huts, (Figure 22), are divided into two districts and back onto the doline walls. Though not much remains of the huts the foundations are still visible. The origins of this village remain a mystery. In fact the building technique differs from the traditional method used in the other Nuragic villages. However, it is believed to date to the late Nuragic age and may coincide with the Roman conquest of the island.

Discovered in the late 1800s during wood clearing in the area, the village was more or less intact and consisted of two groups of truncated cone and rectangular huts built of mud and stone with juniper lintels. Here perhaps the Nuraghe civilization resisted Roman invasion for centuries. Little now remains of this archaeological site, sacked by tomb robbers and trampled by visitors from the 1930s onwards. The atmosphere, the colours of the limestone and the centuries-old holm oaks make this site a unique and unforgettable place.

Apart from the Nuragic village, a large and beautiful cave also cuts into the heart of Monte Tiscali. The cave has two entrances. One is very high up, and can only be reached via an 80 m descent by rope. The second entrance leads into a widened passage that after a few metres opens up into the main room, the sheer size of which leaves visitors in awe. High above is the upper cave entrance through which, at around midday, a ray of sunlight penetrates, illuminating the whole chamber with its huge and fabulous concretions.

DAY 4

Stop 4.1:

From Su Gologone to Nuoro (20 km).

General information on the itinerary

The route proceeds along the paved road.

Recommended maps

Topographic maps – IGM Tables 1:25,000, series 25: 500 sect. IV Nuoro Est, 499 sect. I Nuoro Ovest.

Geological maps – Sheet 1:100,000: 208 Dorgali, 207 Nuoro.

Nuoro is a lively city (Figure 23), whose economy is based on the services sector and commerce.

The town rises on the edge of a plateau in the heart of the Barbagia region, and commands a stunning panorama of the surrounding mountains.

The city was originally divided into two districts, following the typical lay out of the mountain villages

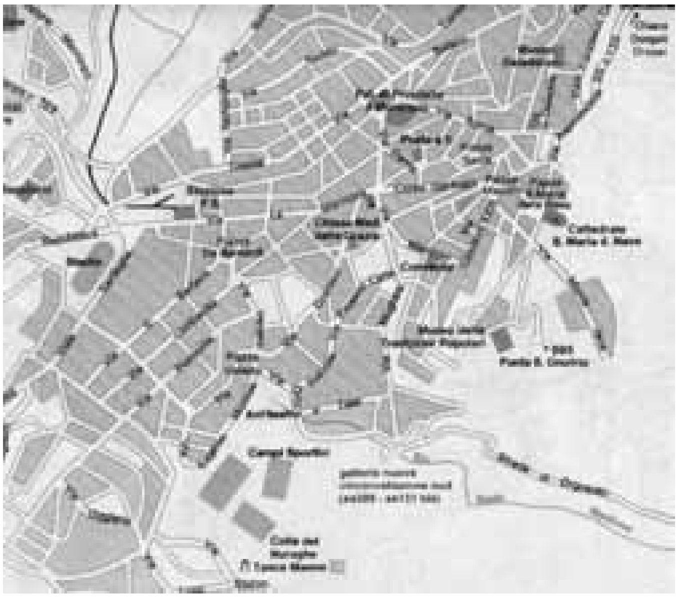

Figure 23 - Map of the historic centre of Nuoro.

Figure 24 - Museum of Sardinian Costumes and Folk Traditions.

in the Barbagia region. The Seuna district in the lower part of the town (where the farmers lived) and the Santu Pedru district in the upper part (where the shepherds lived), joined by the main road, today the Via Lamarmora and Corso Garibaldi.

The newer parts of the city have been built along these two main roads which continue to be the city's central axis, bustling with life and packed with shops. The two roads meet in the square where Our Lady of Graces Church is situated and from where the old 17th century church of the same name can be easily reached.

Leading off this square is Viale Manzoni. Proceeding along this road and then along Via Leonardo da Vinci we come to the Archaeological Museum which houses a number of interesting Roman, Nuragic and paleontologic finds from the Barbagia region and from the Nuoro province.

Figure 25 – Grazia Deledda's house-museum.

Proceeding along Via Giovanni XXIII, and on past the public gardens to Piazza Vittorio Emanuele, with the permanent exhibition of Sardinian Handicrafts on the right, further uphill we come to the airy Piazza of S. Maria della Neve, which is dominated by the majestic Neoclassical facade of the Our Lady of the Snow Cathedral.

Bearing right we eventually reach the Sant'Onofrio hill: at the top of the hill, in a wonderful panoramic position with a stunning view of the city, is the Museum of Sardinian Costumes and Folk Traditions with its precious collections of costumes, jewellery, furniture, rugs and antique objects associated with Sardinian traditions (Figure 24).

Lastly, going back to piazza S. Giovanni, we come to the characteristic San Pietro district, with its narrow winding passageways some of which have been resurfaced using the original pebbles. Worth visiting are the small 17th Century S. Carlo church and Grazia Deledda's House Museum, the famous writer born in Nuoro who won the Nobel prize for Literature in 1926 (Figure 25).

Stop 4.2:

From Nuoro to Monte Ortobene (8 km).

General information on the itinerary

The route proceeds along the asphalted road.

Recommended maps

Topographic maps – IGM Tables 1:25,000, series 25: 500 sect. IV Nuoro Est.

Geological maps – Sheet 1:100,000: 207 Nuoro.

Interesting excursions can be made not far from the city itself. Not to be missed a visit to Monte Ortobene, a granite tectonic block that can be reached by proceeding along Viale Ciusa past the charming Church of the Solitude, where Grazia Deledda is buried. The road climbs uphill past some cool springs eventually reaching the thick holm oak forest that covers the northern mountainside.

The Ortobene mountain consists of normal granite, quartz, orthoclase, oligoclase, biotite, and muscovite being the main components. The medium to coarse grained granite is locally porphyritic.

In the early 1970's, the small catchment of Sedda 'e Ortai (0.414 km^2), on the southern side of the mountain, was chosen as a pilot basin for a systematic campaign of hydrogeological investigations in the granite areas of the island (Barrocu & Larsson, 1977). The bottom of the catchment is cut by a small NW-SE flowing river and bordered by a steep horse-shoe rocky barrier.

The granite is locally intersected by a lamprophyric, SW-NE trending, subvertical dike at least 4-5 m thick, which crops out along the road and has been identified magnetic surveying.

The bottom of the basin is covered with a weathered granite overburden, increasing in thickness towards the outlet, where the bedrock suddenly outcrops.

Monte Ortobene is a tectonic block, uplifted between the grabens of Rio Marreri - Isalle, to the north-west, and Oliena, to the south. The block is split into several minor blocks with varying degrees of vertical displacement. The block is mainly affected by shear stresses, due to post-crystalline shear deformation, tension fractures being less relevant. The major shear families strike N20°W-S20°E and N60°W-S60°E, and are sub-vertical. NE-SW verging overthrusts have NW or SE dip ranging from 0-40°.

The maximum elevation of the basin is 920 m a.s.l. Annual total rainfall of 650.2 mm was recorded in a rain gauge situated at 715 m a.s.l.

From the hydrogeological point of view, and based on the results of geophysical surveying carried out with refraction seismic, geoelectric, electromagnetic and magnetic methods, and of drilling campaigns, the basin is believed to be divided by the two almost-equally-spaced shear fracture systems, into a mosaic with interconnected secondary fracture systems. Natural groundwater reservoirs depend on the rotational effects of the separated small blocks, due to shear movements. Drillings operations were concentrated in a 15 m wide low velocity zone of 2800 m/s, considered to be the most promising.

Based on the results of pumping tests in the wells, a storativity of 0.05% was calculated, corresponding to an estimated bed storativity of about 4÷7,000 m^3/km^2.

The storage capacity of fractured rocks depends on the volume of fractures and on the disintegration and alteration of the rock.

Groundwater composition at Monte Ortobene is strongly affected by wind-borne salts from the sea, like elsewhere in Sardinia. In fact the Na^+/Ca^{2+} ratios may represent the sodium to calcium ratio in the plagioclase of the rock, which should be an oligoclase ($Ab_{80}An_{20}$).

At Nuoro the wind-borne sea salts account for almost half, the other half coming from rock weathering. In similar pilot areas on the coast sea salt accounts for around 75%.

Stop 4.3:

From Monte Ortobene to Arborea (106 Km).

General information on the itinerary

The route proceeds along the asphalted road.

Recommended maps

Topographic maps – IGM Tables 1:25,000, series 25: 538 sect. I Terralba.

Geological maps – Sheet 1:100,000: 217 Oristano.

Just 70 years ago Arborea was a vast expanse of uninhabited and unhealthy wetlands. It was dotted with rivers, water courses, and more than 50 lagoons and marshes, where malaria thrived. The whole area was infested with insects, snakes, tarantula and scorpions and its nickname "Ala Birdis" (the devil's wings) was no exaggeration.

Land reclamation work got under way in 1919 in the area between the S'Ena Arrubia lagoon to the North the Sassu lagoon to the East and the San Giovanni lagoon to the South and was completed in 1928. In 1937, when the large Sassu salt marsh was dried out another 3000 hectares of land was reclaimed for agriculture use and animal raising.

The reclamation was hailed as a major engineering agronomic feat, and also as a miracle. The complex irrigation system designed (irrigation channels and water scoop) knew no precedent elsewhere in Italy. Likewise the modern electro-hydraulic pumps installed in the water scoop on the Sassu salt marsh, in itself an extraordinary architectural monument, had never been used in similar circumstances.

A major effort was required to combat the insects, especially the mosquitoes, using both chemical and biological means. Artificial bat roosts were placed at different points in the reclamation area and the bats multiplied rapidly contributing significantly to defeating the malaria carrying mosquitoes.

Figure 26 - The old town of Arborea.

The newly created farmland was handed over to peasants from the North of Italy and a minor part to Sardinian farmers. Large farms began operating connected by a dense road network and cereal, horticultural crops, water melons and strawberries were grown, and continue to be so today.

In 1928 during fascist times, the first village called "Mussolini's village" was built in the centre of the reclaimed land (Figure 26).

At the time Arborea counted a thousand inhabitants, increasing to 2253 in 1930, when the municipality of Mussolinia was founded, and to 3800 in 1936. At the end of the Second World War, the name of the village was changed to Arborea.

Today, the modern farming centre of Arborea can boast the highest agricultural and animal productivity in Sardinia. The territory extends over an area of some 115 km^2 with a population of around 3990 inhabitants.

Today the orderly landscape is a succession of cultivated fields divided by rows of poplars and eucalyptus trees and of modern stables.

Figure 27 - S'Ena Arrubia lagoon.

Figure 28 - The Oristano plain.

The numerous canals that cross the Arborea plain are essential for sustaining agriculture and the enormous, strategically situated water pumps distribute irrigation water all over the territory.

The numerous pinewoods in the area serve to hold the sandy soils in place and to shelter the crops from the furious mistral wind.

Worthy of mention are the lagoons surrounding Arborea. These are of significant natural value and the pink flamingos make this an annual stopover on their journey between Africa and France. The lagoons are also home to numerous other bird species (Figure 27).

The Oristano plain in central-western Sardinia is part of the Campidano alluvial plain and occupies a belt that extends from the sea to the West up to the Monte Arci mountain range (812 m) to the East. The study area is bounded to the North by the Rio Mannu at Santu Lussurgiu and to the South by the Rio Mogoro (Figure 28). The plain is crossed by the 150 km long Tirso river, the most important river in Sardinia with a drainage basin of 3.376 km^2 (Fadda & Pala, 1992). All the rivers in the plain flow out into the Gulf of Oristano or into the numerous coastal lagoons, the most important ones being Cabras, Mistras, Santa Giusta, S'Ena Arrubia and San Giovanni. The area

Figure 29 - Geological map of the Oristano plain. Holocene: 1. Present and recent beach sands passing to coastal dunes; 2. Pebbly-sandy or clayey alluvia and clayey silt palustrine or brackish deposits. Pleistocene: 3. More or less cemented dune sands; 4. Pebbly-sandy alluvia covered primarily with (ancient) relict dunes; 5.Pebbly terraced alluvial deposits with interbedded sand,; 6 Pebbly alluvial deposits of the upper terraces.

still presents several depressions, former marshland, that today have been largely reclaimed.

Geomorphology

The Oristano plain formed on the Campidano Graben. It has a practically level surface and lies at an average elevation of about 10 m a.s.l. Despite the monotonous landscape the plain exhibits relatively complex characteristics. The northern portion is characterized by two alluvial deposits, one overlying the other, while the southern part is occupied by recent alluvium of the Rio Mogoro. The depressed parts were constantly prone to flooding before the river banks were raised (Fadda, 1990).

The last sedimentation phase produced a succession of gravel, sand, silt and clay deposits (Barrocu et al., 1995). Eolian sands have also deposited creating a coastal dune system that locally reaches a height of 8m. In the Arborea and Santa Giusta areas lies the largest expanse of sand dunes in Sardinia. Figure 29

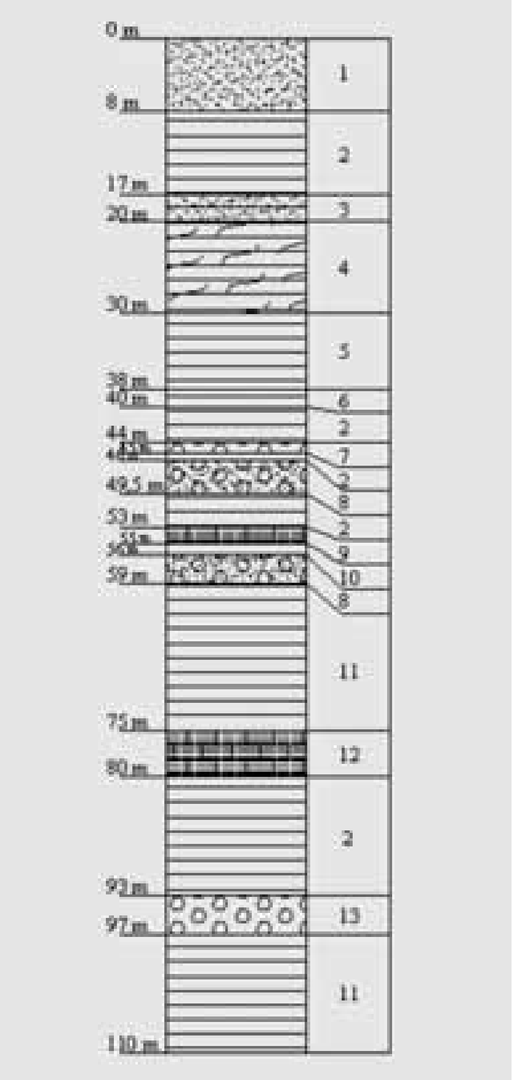

Figure 30 – Stratigraphy in the Arborea area. 1:Fine yellowish sands interbedded with clay hosting phreatic aquifer; 2: blackish clay; 3:sandy clay hosting aquifer of moderate yield; 4: blackish silty clay; 5: black clay; 6: blackish clay containing shell; 7: pebbly clay; 8: pebbly layer with sand with aquifer under pressure; 9: marly clay; 10: sandy clay; 11: grey clay; 12: grey marly clay; 13: gravelly layer with aquifer under pressure.

Figure 31 - Isosalinity curves (µS/cm) for the surface aquifer (after Salis & Soddu, 2003).

shows the geological map of the study area.

Hydrogeology

A phreatic or semi-confined aquifer hosted in sand and gravel has been identified in the area. The aquifer bed lies at a depth of between 8 and 11 m, and overlies a series of confined or semi-confined aquifers of varying thickness, composed of a succession of sand/gravel and clay. The surficial aquifer and the multi-layer aquifer are separated by a layer of clay of variable thickness. However, in several points the aquifers have become interconnected due to the effects of short-circuiting as a result shoddy well construction. Figure 30 shows the stratigraphy of a core drilled near the town of Arborea.

A number of exploration boreholes drilled in the area suggested that the multi-layer aquifer is situated at depth of more than 500 m.

The river Tirso has been dammed upstream and concrete embankments have been built on most of the smaller rivers. As a result, river runoff into the aquifers has diminished drastically.

For example after concrete embankments were built along the Rio Mogoro, most of the wells dried up. At present the aquifer system is fed by direct infiltration due to the residual runoff, rainfall and irrigation, and by lateral inflow from the volcanic rock aquifers bordering the plain. Based on the water budget calculated for the plain (Staffa, 2003) aquifer recharge has been estimated to be 298 mm/year.

Saltwater intrusion

Monitoring in the northern part of the plain was commenced by the Department of Land Engineering at Cagliari University in 1990, but data collected back in 1979 were retrieved and analyzed 1979 (Barrocu et al., 1995). In early 2003 the study was extended to the southern part of the plain and a monitoring network set up comprising more than 200 shallow and deep wells, chosen from among the inventoried wells. Earlier data were re-organized and a data base set up. Analysis of the data, consisting in pH, electric conductivity, temperature and water level measurements, conducted with a GIS, has shown groundwater resources to have been poorly managed. Groundwater overabstraction to meet the increasing municipal and agricultural water demand during the prolonged droughts that have afflicted Sardinia over the last few years, have resulted in saltwater intrusion

Figure 32 - Isosalinity curves (µS/cm) for the deep aquifer (after Salis & Soddu, 2003).

Figure 33 - The ruins at Tharros.

in increasingly larger areas.

The determining cause is to be sought in the gradual lowering of the groundwater table. In those surficial aquifers where the water table has dropped significantly, an increase in groundwater electric conductivity has also been observed. Water table lowering is more pronounced in the summer months and less pronounced inland.

Water levels indicate both for the surficial and deep aquifers that the groundwater flows primarily from inland towards the coast, with local inversions due mainly to the presence of pumped wells. Note that the hydraulic gradients also diminish towards the coast.

Figures 31 and 32 show the salinity contour lines for the surficial and deep multi-layer aquifers measured in spring 2003.

As can be observed, salinity levels throughout the plain are well above the 400 µS/cm established by Italian Law for drinking water and in vast areas exceed 2000 µS/cm, the limit value for the majority of crops grown in the area.

The isosalinity curves in the surface aquifer exhibit a fairly irregular pattern, the higher values being observed along bands lying pseudo-perpendicular to the coast. This appears to suggest that preferential pathways exist, probably consisting of formations with higher permeability through which the seawater encroaches inland.

Concerning the multi-layer aquifer, the highest salinity values have been observed along the coast, and local anomalies have also been found inland.

This suggests that the cause of salination may be attributed to seawater intrusion only in the coastal area. Inland, the salinity may be caused by other phenomena such as upconing, dissolution of unleached salts present in the aquifer formations and the presence of subsurface seawater that has infiltrated through the ground in past geological eras.

As can be observed in the deep aquifer the salinity peaks are higher than in the surficial one but only in small zones, electric conductivity remaining below 1000 µS/cm in vast areas. Furthermore the most contaminated areas were found south of the S’Ena Arrubia lagoon and along the River Tirso mouth. In the latter area high electrical conductivity was also observed in the surficial aquifer.

Summing up, monitoring and the hydrogeological studies carried out in the plain allowed us to:

- ascertain the existence of groundwater salination processes and track their temporal evolution;
- identify the most vulnerable zones; in particular it has been observed that on the whole the surficial aquifer is more severely contaminated than the deeper one.

Based on the hydrogeological data and hydrogeochemical and isotope analyses, a GIS supported model has been developed. Using a three-dimensional finite element code (CODESA 3D), simulating coupled flow and solute transport processes in variably saturated porous media, a model has been defined, by means of the calibration-validation process, that can also be used for predictive purposes, aimed at integrated water resources management.

DAY 5

Stop 5.1:

From Arborea to San Giovanni di Sinis (10 Km).

General information on the itinerary

The route proceeds along a paved road. One-hour guided visit to the archaeological site at Tharros.

Recommended maps

Topographic maps – IGM tables 1:25,000, series 25: 528 sect. I Cabras, II Oristano, III Capo San Marco.

Geological maps – Sheet 1:100,000: 216 Capo San Marco, 217 Oristano.

The remains of the ancient city of Tharros at San Giovanni di Sinis (Figure 33), are one of the most important archaeological sites in the Mediterranean.

Tharros was founded in the VIII century B.C. by the Phoenicians, but the area was previously inhabited by the Proto-Sardinians. Following Phoenician domination, the town became a Roman settlement. But it was thanks to the Carthaginians that Tharros took on an organised urban structure in the VI century B.C. The Romans settled in the area around 238 B.C., leaving the former urban structure intact, expanding the city around the existing buildings.

During the Roman Empire the territory became a colony but, from the V century onwards, was raided by the Vandals. During the Byzantine domination it became the Bishop's headquarters. Between the VIII and IX century the Saracens also staged a series of incursions. The inhabitants were eventually forced to leave the town in 1070, after a short return in 1052.

Excavations during the last century by Italian and later French and English archaeologists brought to light the remains of the town. In fact part of the finds discovered are currently conserved in the British Museum in London and in the Borely Museum in Marseille.

Of major importance are the paved Roman roads and other evidence of Roman occupation, such as the tombs, the aqueduct, the water tank, the bath houses with the remains of three systems complete with dressing-rooms, saunas, pools with hot and cold water, the temples, the living quarters, and the premises where the craftsmen worked coral. Between the V and the III century B.C. they also used to work iron, and in fact a number of furnaces have been discovered where the metal was melted at very high temperatures.

The Proto-Christian church, Phoenician necropolis and monolithic temple dating to the Punic period carved into the sandstone rock are also of great interest.

To the NE of the excavated areas stand two altars of the tophet, where the Phoenicians were thought to have sacrificed children, even though today they are believed to have sacrificed animals, and placed there children who died of natural causes. Near the archaeological site there is also a Nuragic village.

Figure 34 – Flamingos.

The site is situated in a beautiful setting, enhanced by the nearby sea and sand dunes. To the North of S. Giovanni di Sinis are the splendid sandy beaches of Is Aruttas and Mari Ermi composed of tiny quartz granules.

Aside from the cultural and tourist attractions, the lagoon at Cabras, one of the largest in Europe, is an important nature reserve of major environmental significance. Its banks are populated with aquatic birds, including pink flamingos (Figure 34) and the lagoon abounds with highly sought after species of fish.

Stop 5.2:

From San Giovanni di Sinis to Villacidro (58 Km).

General information on the itinerary

The route proceeds along the asphalt road.

Recommended maps

Topographic maps – IGM tables 1:25,000, series 25: 547 sect. III Villacidro.

Geological maps – Sheet 1:100,000: 225 Guspini.

Because of its position, nestled between the rocky eastern spurs of the lglesiente range, Villacidro is described as the only "mountain" town in the Campidano. In the charming old centre stands the art nouveau public fountain. Various excursions can be made into the mountains, starting from the State forests at Montimannu.

The rugged slope borders with M. Linas and is thickly wooded. The Rio Muru Mannu and Rio Linas waterfalls are the highest and most spectacular in Sardinia.

From the summit of the reliefs, one can enjoy a magnificent view of the entire Campidano plain and the lglesiente and Sulcis mountains as far as the sea. Nearby are the archaeological remains of a Punic temple, Nuraghe huts and three temples with wells, which are hidden from view. A kilometre and a half from the town, is the waterfall of Sa Spendula.

Villacidro is situated at the mouth of a small catchment surrounded by the steep mountains of M. Omo to the North, M. Cuccuru Frissa to the South, and M.s'Enna de is Forrus to the West. During the dry season, the basin is drained eastwards by a small stream. In the upper part of the valley there are several springs, developed for the town's water supply. At the mouth of the valley are some shallow wells and some groundwater seeps into the river bed. In the middle of the valley no springs or groundwater seepage are evident.

The summits of M.Omo and s'Enna de is Forrus consist of hornfels schists of Devonian to Carboniferous age, produced by thermal metamorphism of shales and phyllites at the contact with the granite (Barrocu et al., 1974).

A medium- to coarse-grained granite occupies the lower part of the area, gradually passing to microgranite at the summit. Generally, the coarse-grained granite appears more weathered than microgranite. The two types differ only in texture, as both consist of quartz, orthoclase, biotite and muscovite.

Both the granite complex and schists are crossed by swarms of small quartz veins, usually 1-3 m wide. A vertical, 1-m-wide, N85°E-S85°W-striking vein is locally mineralized with Pb, Zn, and oxidized ores.

The granite rock body is dissected by a joint system, indicating that the granite was deformed, probably rather close to its intrusion, in a N-S direction. This deformation gave rise to stress in E-W direction producing a series of frequent, approximately N-S trending narrowly spaced tension cracks ("ac-joints").

The area forms part of the western flank of the Campidano Graben of south-western Sardinia. Along this flank a rather connected tectonic pattern appears in the rocks. Lateral as well as horizontal movements were released as distinct fracture zones. Thus shear movements along approximately N-S fracture planes dissected the rock almost perpendicularly to the longitudinal axis of the valley of Villacidro. Obviously, these movements, associated with the Campidano tectonics, were steered in this direction by previously existing ac-joints. Along the sides of the valley shear joints are frequent, showing secondary movements along the direction of the valley.

According to the basic theory for groundwater occurrence in hard rocks, major fractures are presumed to contain groundwater. However, earlier investigations had demonstrated that shear fractures caused by weak shear movements, are very often compressed and consequently tight, or in any case make poor aquifers. On the other hand, shear zones with major displacement were found to be so heavily brecciated as to be considered gravel structures. In this case they act as highly productive aquifers, especially when rotational movements have occurred during the shear process. In fact, rotation very often opens up the fracture zone, increasing total free pore space significantly.

According to our working hypothesis, both tight and open shear fractures occur in the valley of Villacidro. The tight shear is presumed to have occurred along the bottom of the valley, indicated by secondary shear planes on the rocky sides of the valley. The open shear is thought to have cut the valley, almost perpendicularly, between two blocks. This assumption, based on the result of seismic surveying, was confirmed by drilling operations carried out in a low velocity zone in the middle of the valley. A borehole drilled down to -65 m in the tight shear zone yielded only 0.13 l/s (470 l/h). The cataclastic granite was weathered down to -55 m.

An inclined well (75°) was drilled in the valley bottom in a zone located by extrapolating the direction of the shear between the two blocks in the northern side, so as to strike the fracture zone below the assumed groundwater table, at a depth of about 20 m. The fracture zone was struck by the inclined borehole at -41 m; drilling operations had to be interrupted at -51.7 m, in the fracture zone, because of the strong groundwater inflow. The well pumped for 30 hours with a stable drawdown of 13 m gave 0.5 l/s (1800 l/h). A vertical borehole drilled in the same fracture zone yielded 1.1 l/s (4000 l/h) with a stable drawdown 20 m below the natural water table.

Stop 5.3:

From Villacidro to Capoterra (46 Km).

General information on the itinerary

The route proceeds along a paved road.

Recommended maps

Topographic maps – IGM tables 1:25,000, series 25: 565 sect. I Capoterra, 566 sect. IV La Maddalena, 557 sect. III Cagliari, 556 sect. II Assemini.

Geological maps – Sheet 1:100,000: 233 Carbonia, 234 Cagliari.

A comprehensive study of the Capoterra alluvial plain has been carried out by the Engineering Geology and Applied Geophysics Section of the Department of Land Engineering at Cagliari University, within the frame of the international projects MEDALUS and AVICENNE 73, funded by the European Union. The purpose of the investigation was to gain a deeper insight into saltwater intrusion in the coastal aquifer system and to numerically simulate the phenomenon (Sciabica, 1994; Barrocu et al., 1997, Barrocu et al., 1998).

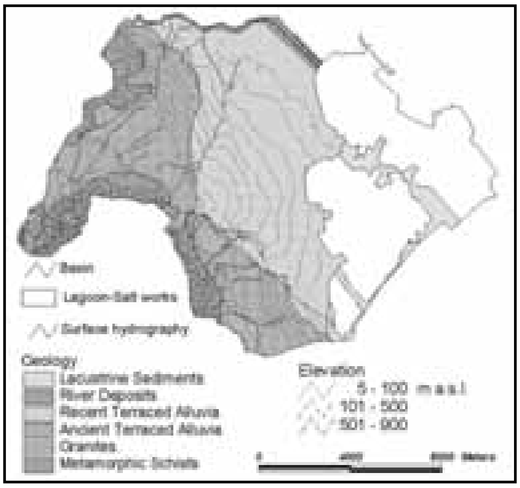

Figure 35 - The Capoterra alluvial plain.

On account of the large amount of data collected for the Capoterra alluvial plain, a Geographical Information System (G.I.S.) was set up, creating an alphanumerical database together with a geographic database, so as to allow for integrated methods in modelling saltwater intrusion in the coastal aquifer system (Barrocu et al., 2001).

Field investigations and monitoring network

The Capoterra alluvial plain is situated in the south-western portion of the Campidano Graben in southern Sardinia. It comprises, to the South, the delta of the Santa Lucia river, a torrential watercourse, and is bounded eastwards by the Santa Gilla lagoon and northwards by the Cixerri river. To the West it is interrupted by a series of hills aligned en échelon, representing the extension of the tectonic block that west of the Sardinian Graben is split up by two main sets of NW-SE and NE-SW trending fractures (Figure 35).

Based on the geological, hydrogeological, geomorphological, and pedological information for the area, the following hydrogeological units have been identified (Barrocu et al., 2000): fluvial and lacustrine sediments, recent and ancient terraced alluvia of the Quaternary and fractured granites and metamorphic schists of the Palaeozoic. The recent alluvia are highly permeable and contain a phreatic aquifer, overlaying a second multi-layer aquifer, semi or locally confined.

Over the last two decades, the area has undergone profound transformations due to agricultural and industrial expansion and water demand has increased accordingly. The particular climatic conditions of the area, characterized by frequent and prolonged periods of drought, as well as the presence of various natural and anthropogenic sources of salt (sea spray, sea water, lagoon, evaporation ponds from the salt-works and salt-hills), combined with indiscriminate overexploitation, have resulted in the depletion of groundwater resources and in their widespread salination, with more serious effects in the shallow part of the coastal aquifer system. A monitoring network for controlling water quality and groundwater level was set up in June 1991, initially in the southern portion of the plain, near the Santa Lucia river, and then extended northwards in April ’92 so as to include the area nearer the Cixerri river. In 1991, ’92 and ’93, groundwater levels were measured each month in all the wells and water samples collected from some significant wells were chemically analyzed in the laboratory.

Pumping tests were performed at selected observation wells or at purposely built wells and piezometers so as to evaluate the hydrogeological parameters for

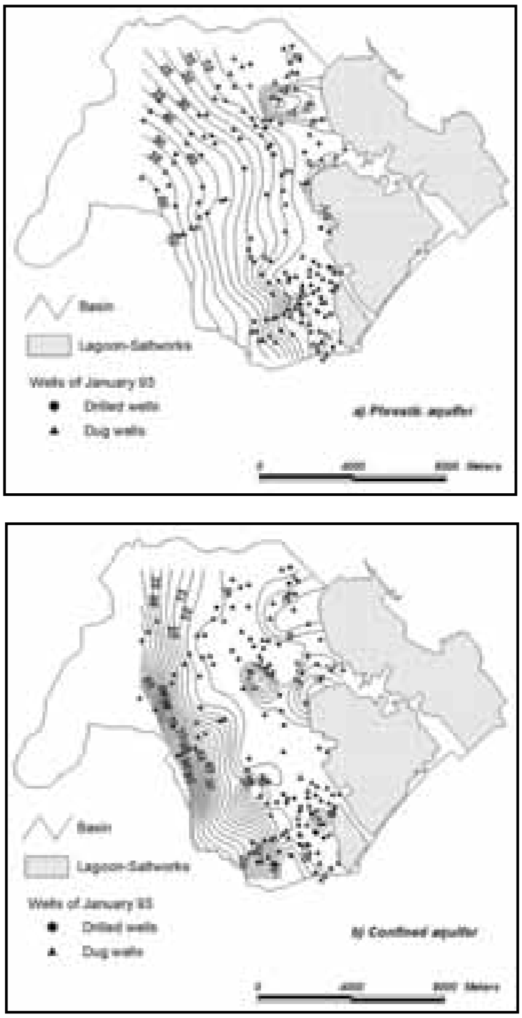

Figure 36 - Water level contour lines (January '93).

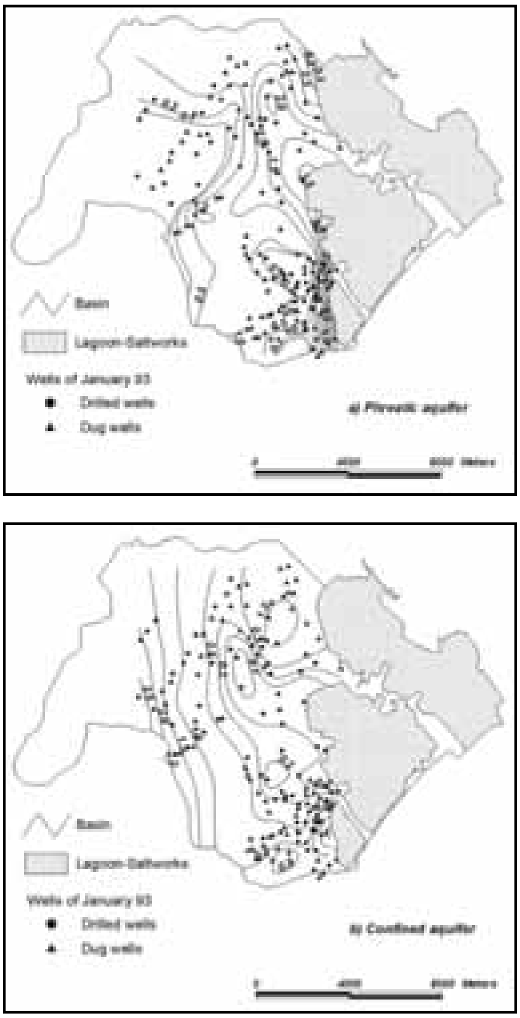

Figure 37 - T.D.S. contour lines (January '93).

simulating saltwater intrusion.

Artificial recharge experiments were also carried out at purposely built wells and piezometers in the plain so as to assess the efficiency of a hydrodynamic barrier aimed at controlling saltwater encroachment and its spatial evolution (Barrocu et al., 1997).

More recently, in July 1998 a measurement campaign has been conducted in the frame of a detailed study of the groundwater geology and geochemistry (Vernier, 1999).

Hydrogeological and hydrogeochemical investigation results

The hydrogeological and hydrogeochemical data, collected during measurements taken in the control and monitoring network, were used for constructing graphic representations such as piezometric contour lines, Schoeller's diagram, Chebotarev's diagram, T.D.S. contour lines, and so on (Barrocu et al., 1994, Barrocu et al., 1994).

The water level contour lines for January '93 (Figure 36) show that both aquifers are recharged laterally by groundwater through the granite bedrock at the western boundary of the aquifer. Supply probably takes place through preferential pathways in the form of the main fracture systems occurring in the bedrock. In both aquifers there is a depression of piezometric surface to below mean sea level coinciding with groundwater over-exploitation to satisfy agricultural and industrial demand. Depressions are located

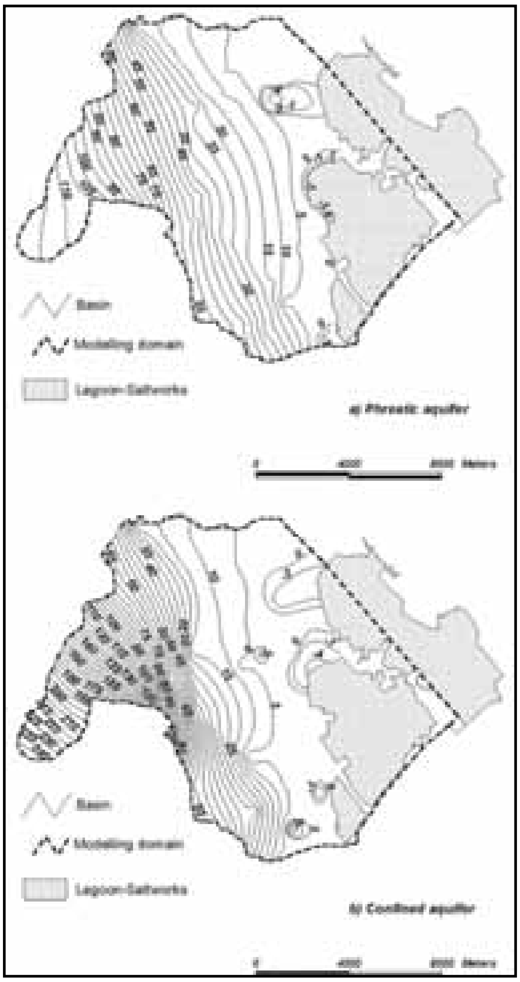

Figure 38 - Calibration-validation of flow equation (January '93).

mainly in the central part of the plain, near the lagoon and the saltworks. Low piezometric levels were also observed in proximity of the coast.

Figure 37 shows the January '93 T.D.S. contour lines for both aquifers. Recharge into the phreatic aquifer from the western side is indicated by the lowest salt content; to the south (coastal zone) and to the east (where the saltworks and lagoon are located) the values increase, coinciding with the lowest piezometric heads. Salination in the eastern portion of the plain and near the border with the saltworks remains practically unchanged throughout the year. In summer the situation near the coast is exacerbated by the increase in irrigation demand. In the main, the deep aquifer is not as salinated as the phreatic one. In the central part of the plain, where intense groundwater abstraction results in significant depression of the piezometric surface, salinity remains low all year round, while in the western part of the plain it exhibits an increasing trend.

Modelling saltwater intrusion

The modelling procedure applied for simulating saltwater intrusion processes in the Capoterra coastal aquifer system involves the definition of the hydrogeological and conceptual models, formulation of the mathematical model, its numerical solution and validation using field measurements and chemical determinations (Sciabica, 1994). If the model is not satisfactorily validated, adjustments will have to be made at the various modelling stages and further simulation performed, repeating this procedure until the model has been successfully validated.

The hydrogeological model has been defined by identifying both the natural factors, such as geology, proximity of the sea, presence of the lagoon and saltworks, and anthropogenic factors including irrigated agriculture and the urban and industrial development of the study area. The relationship between groundwater, lagoon, saltworks and sea has been established by processing piezometric data. Processes influencing water salinity in the coastal aquifer system were elucidated by examining the correlation between chemical elements present in the water samples.

The conceptual model has been defined by simplifying the domain and the phenomenon under study, introducing several assumptions concerning dimension and geometry of the domain, composition and properties of the porous medium, processes that take place within the domain.

The mathematical model can be formulated as a coupled system of two partial differential equations, one describing mass conservation for the water-salt solution (flow equation), and the other mass conservation for the salt contaminant (the transport equation). Flow and transport equations are coupled by means of the constitutive equation relating density of the freshwater-saltwater mixture to salt concentration. Initial and Dirichlet, Neumann, or Cauchy boundary conditions are added to complete the mathematical formulation.

The numerical solution code of these non-linear equations involves spatial discretization using the finite element method according to Galerkin's approach, and time discretization using finite differences; the non-linear coupling is resolved

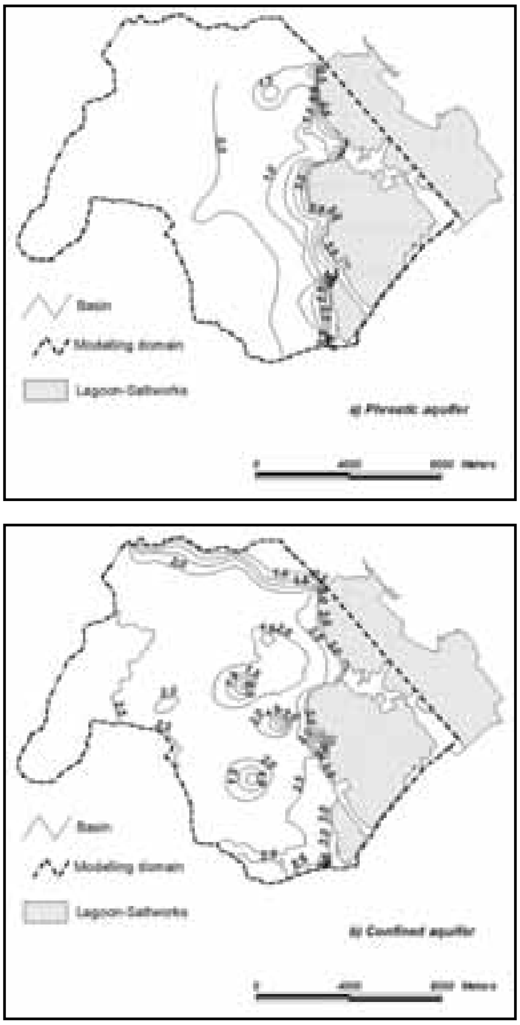

Figure 39 – Calibration-validation of transport equation (January '93).

using a Picard iteration method, which subsequently solves the flow and transport equations (Sciabica, 1994; Paniconi and Putti, 1995). The results from the numerical code are expressed in terms of equivalent freshwater heads and normalized concentrations at selected time intervals and at each node of the three-dimensional mesh.

The calibration-validation of the numerical solution code is performed by comparing the simulation results with hydrogeological and hydrogeochemical data obtained from the monitoring network (Sciabica, 1994, Barrocu et al., 1997, Barrocu et al., 1998).

The water level contour lines for January '93 could be fairly well reproduced with our calibration-validation procedure. Figure 38 shows the lateral recharge from the western boundary of the domain, the preferential flow direction towards the lagoon, the saltworks and the sea, and the zero contour line coinciding with the drawdown cones of some wells near the lagoon (phreatic aquifer) and the saltworks (confined aquifer).

The T.D.S. contour lines plotted using the calculated data (Figure 39) and the field data for January '93 show a similar trend.

Organization of the G.I.S.

On account of the large amount of data collected for the Capoterra alluvial plain a Geographical Information System (G.I.S.) was set up, creating an alphanumerical database together with a geographic database (Barrocu et al., 2001).

The information collected in the monitoring network over the years of measurements was organized into an alphanumeric database, created with Microsoft Access software. To facilitate input, modification and above all the display of the information contained in the database, masks were created for "coordinates and elevations", "water levels" and "chemical analyses" for each month of measurement, and "pumping tests", linked together by action keys. In each mask it is possible to search for information concerning a specific well, to access the other masks, to print the report of the data, after preview, and to return to the last mask displayed.

The geographic database, created with ESRI Arc Info and Arc View software, organizes all the information collected in the Capoterra alluvial plain into a number of views and themes:

- a view that contains levels of general information that were created from .DXF files in AutoCAD and imported and converted into ArcInfo coverages and ArcView shape, i.e., geology, elevation, surface hydrography, monitoring network;
- as many views, constructed querying the Access database by using an SQL connection feature, as there are months of measurement, containing the information on water level, T.D.S. and electric conductivity contour lines of the phreatic and confined aquifers, and the spatial distribution of the principal physico-chemical parameters, such as temperature, pH, cations and anions;

- a view containing the levels of information created from the saltwater intrusion modelling results including the two-dimensional mesh, the equipotential and equiconcentration lines of the aquifers both for the calibration-validation procedure and the simulations.

Over the last 10 years the town of Capoterra and its suburbs has seen one of the highest population increases on the island and a major transformation in town planning. Today its territory is divided up into three distinct settlements about five kilometers apart. The former built up area, the oldest, which expanded around a seventeenth-century village, lies at the foot of the hills of Montarbu, Punta Sa Loriga and Mount Arrubiu. The second runs along the coastal ribbon from Maddalena up to Cala d'Orri and started to be developed in the early 1960s; the third began to take shape in 1966, in the low hills of Sa Birdiera and Pauliara, at the foot of Mount Santa Barbara.

Up to the mid 1800s the economy was based on agriculture and cattle farming.

In 1860, when the S. Leone mine, owned by the Petin Gaudet company from Paris, and proprietor of the "Compagnia degli Alti Forni e Acciaierie della Marina e delle Macchine a Vapore" ("Company of the furnaces and steelworks of the Navy and of the steam machines") went into operation, the inhabitants of Capoterra were maybe the first in Sardinia to witness the amazing innovations of the Industrial Revolution, which had begun in England at the beginning of the previous century. Some of the Capoterra people adapted to working in the new mining complex, first as labourers, then as miners.

This mine, which was sold towards the end of the last century, and remained idle for various periods until its closure in 1963, boosted the economy of this village. Mining operations (even if arduous and a health hazard) gave many families the opportunity to overcome the difficult economic situation at the beginning of this century, when the village was still geographically isolated, and far from the main communication routes. Though relatively close to Cagliari, public transport at the time was practically non-existent and often interrupted when the Scafa bridges collapsed for one reason or another.

In the 1920s the opening of the Macchiareddu saltworks was a great boost to the village's economy It was, however, seasonal work, and worker exploitation was well stage-managed as they were paid by piecework creating ruthless competition among the teams of salt collectors. The agricultural boom during the fascist period was neutralized by the deleterious effects of the war and recovery was not easy.

To make up for this, in the post-war years some traders resorted to the traditional practice of bird-trapping, used in the past during difficult times. With the closure of the S. Leone mine, to cope with heavy unemployment problems in the area bird-trapping was even regulated by a regional law, with the support of the leftwing parties. Today it is prohibited.

The arrival of the petrochemical industry at Sarroch and Macchiareddu again kindled hopes for recovery. But for many years the people of Capoterra were forced to work for contractors, with no safety agreement and low salaries, because lacked proper specialization and because the Employment Agencies of Assemini and Sarroch preferred to give work to their own unemployed.

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Back Cover:
field trip itinerary

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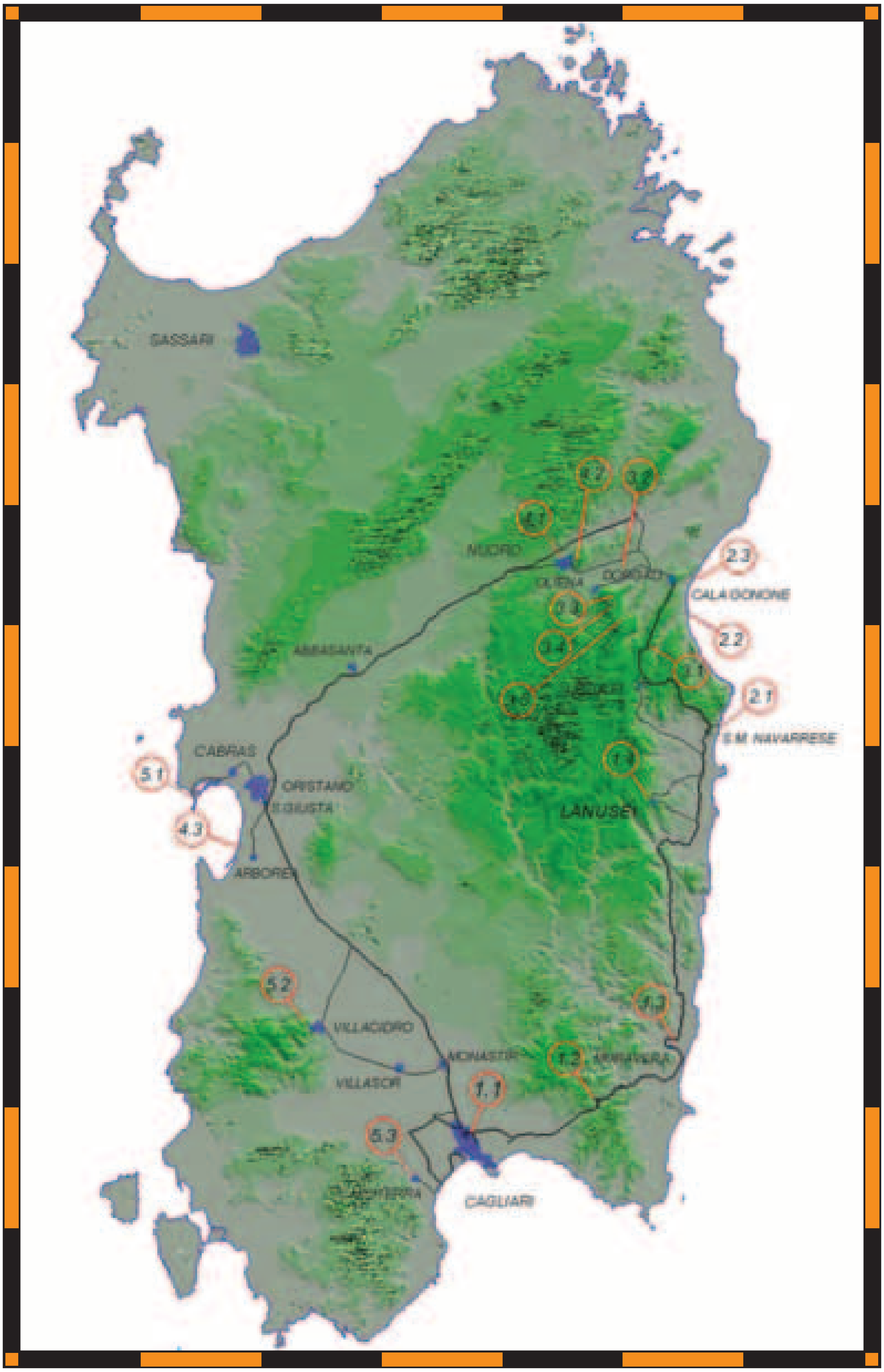
FIELD TRIP MAP



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