Journal of Coastal Conservation 9: 81-90, 2003

Integrated, sustainable touristic development of the karstic coastline of SW Sardinia

Arisci, A.; De Waele, J.*; Di Gregorio, F.; Ferrucci, I. & Follesa, R.

University of Cagliari, Geology Department, Via Trentino 51, I-09127 Cagliari, Italy;
**Corresponding author; Fax +39070282236; E-mail geoam@unica.it*

Abstract. In the coastal karstic region of SW Sardinia, from Capo Pecora in the north to Nebida in the south, many interesting geological monuments, ecotopes and several places of social and cultural interest that deserve preservation and valorization can be found. This mostly rocky coastline is characterized by the presence of a Cambrian sequence prevalently composed of limestones and dolostones and only locally of phyllites. A correct use of the many environmental and cultural monuments is necessary both to preserve and to valorize them; therefore they have to be properly managed in order to preserve their original natural conditions. Here, we describe and classify these monuments with the aim to propose an integrated model of sustainable development of this exceptional coastal landscape. Our model is based on several thematic maps according to which we propose the establishment of a natural reserve with specific geological and geomorphologic sites and the creation of several touristic circuits that are the basis for a further valorization of this territory.

Keywords: Coastal landscape; Ecotope; Geological monument; Geosite; Industrial archaeology.

Introduction

The southwestern coast of Sardinia, stretching from Capo Pecora in the north to Nebida in the south, is one of the scientifically most interesting coastal areas of Sardinia. Until only 20 yr ago the most important economic activities in the region were related to mining, which industry has left considerable traces in the landscape. Recently the people living in these old mining villages are trying to treat the industrial remains as archaeological monuments, and make them a tourist attraction, together with the many geological, ecological and cultural monuments.

In the present paper we describe the most important of these monuments, emphasizing their use in the framework of an integrated model of cultural touristic development.

Geological outline

The coastal karstic region of SW Sardinia forms part of the Cambrian Iglesiente massif, which has been intensively exploited for lead and zinc in the past. The Palaeozoic rocks in the area have been described by Pillola (1989) and Bechstadt & Boni (1996). From a stratigraphic point of view the Cambrian succession in SW Sardinia is divided in three major groups: Nebida, Gonnesa and Iglesias (Fig. 1). The Nebida Group (Lower Cambrian) is composed of a delta and coastal sediments and is divided into two formations: the Matoppa (sandstones and shales) and Punta Manna (oolithic limestones and calcareous sandstones followed by sandstones with carbonatic fossiliferous lenses and strata).

The Gonnesa Group (Lower-Middle Cambrian) is characterized by typically carbonatic deep-sea sediments and is divided into two formations according to its trilobite contents: the Santa Barbara Formation (mainly dolomitized rocks) and the San Giovanni Formation (intensely karstified limestones). In these carbonatic rocks we find most of the Mississippi Valley type ore deposits and their oxidized equivalents with economically important concentrations of lead and zinc minerals, which have been mined.

The Iglesias Group (Middle Cambrian-Lower Ordovician) is divided into two formations: the Campo Pisano Formation, composed of nodular limestones, followed by a thick succession of shales of the Cabitza Formation.
After a long period of continentality and an important tectonic phase (*Fase Sarda*) the sea returned to occupy this area with the deposition of the Ordovician conglomerates (*Puddinga*), followed by Silurian and Devonian sediments. After the Hercynian orogenesis a long continental period started in the region (Carboniferous-Middle Trias), only shortly interrupted by new transgressions in Middle-Triassic and in Paleocene-Eocene times.

The prevailing structures in the coastal area of Capo Pecora-Nebida are folds directed N-S that involve both Ordovician and Cambrian rocks and the great anticline of Canalgrande-Punta Sa Gloria with an E-W direction (Civita et al. 1983).

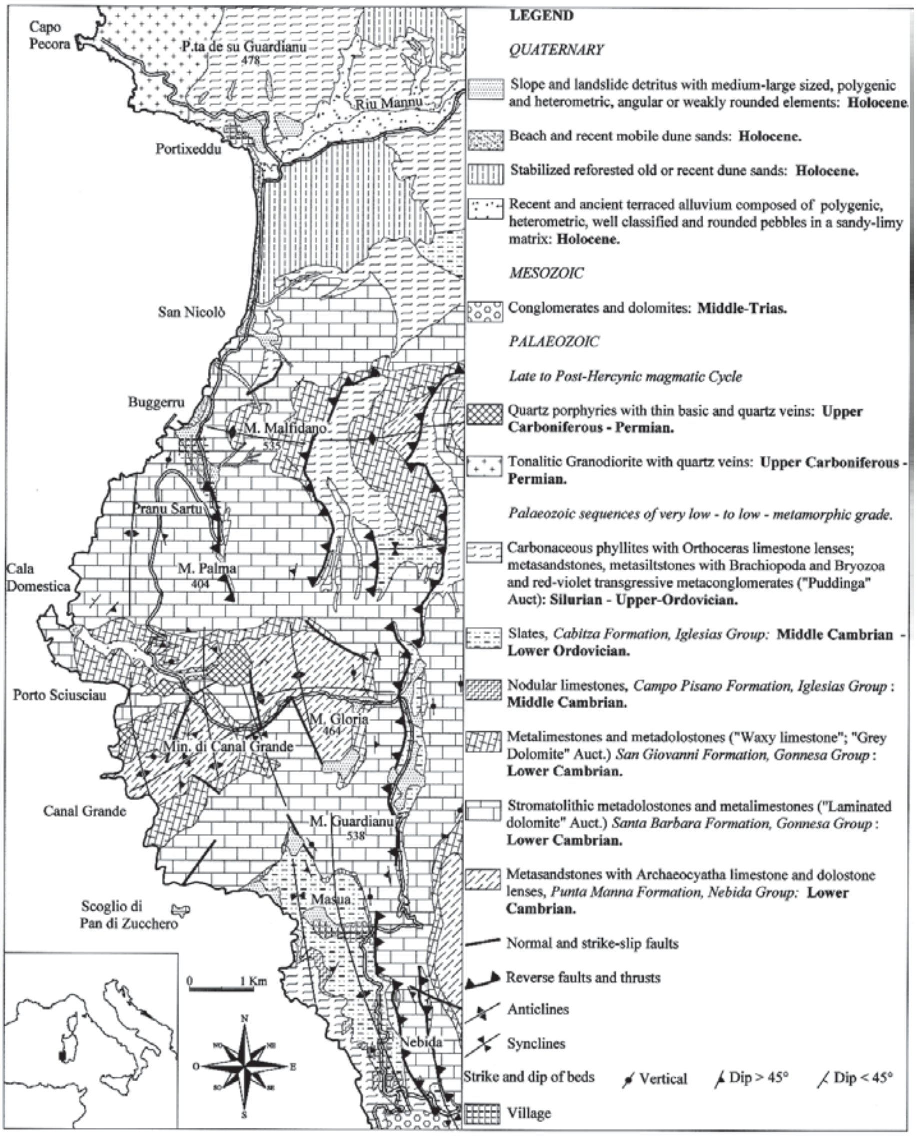

Fig. 1. Geological sketch map of the Capo Pecora-Nebida karstic coastline (modified from Civita et al. 1983).

Geological and other monuments

Fig. 2 presents the most interesting geological, environmental, industrial-archaeological and cultural monuments and sites (Arisci et al. 2001a).

To the north of the studied area lies Capo Pecora, composed of late Hercynian and thoroughly fractured tonalitic granodiorites with a wide variety of colours ranging from pink to grey. These granitic rocks form a promontory, extending to the west and eroded by wind and sea. In spring this area is characterized by the spectacular blooming of the Mediterranean lily *Pancratium maritimum*. Because of the peculiar lithologies and morphologies and the botanical interest this site has been classified as a geological and natural monument (Barca & Di Gregorio 1999).

To the south along the coast the touristic village of Portixeddu is situated; it is built upon the upper part of the Portixeddu Formation (Upper Ordovician), consisting mainly of richly fossiliferous dark-grey siltstones and shales of ca. 50 m thick (Leone et al. 1991). This locality has been known since 1880 for its fossils (brachiopods, bryozoans, cystoids, crinoids, gasteropods, bivalves, trilobites, cornulites, conularids and corals). However, because of the incompleteness of the series and its structural complexity Portixeddu was not chosen as the type locality of the formation (Bechstadt & Boni 1996).

The dune system of Portixeddu extends over an area of ca. 4 km^2 south of the village and is composed of at least three generations of eolian deposits dating from the Middle Pleistocene to the Holocene (Cesaraccio et al. 1986; Arisci et al. 1999). From a morphological point of

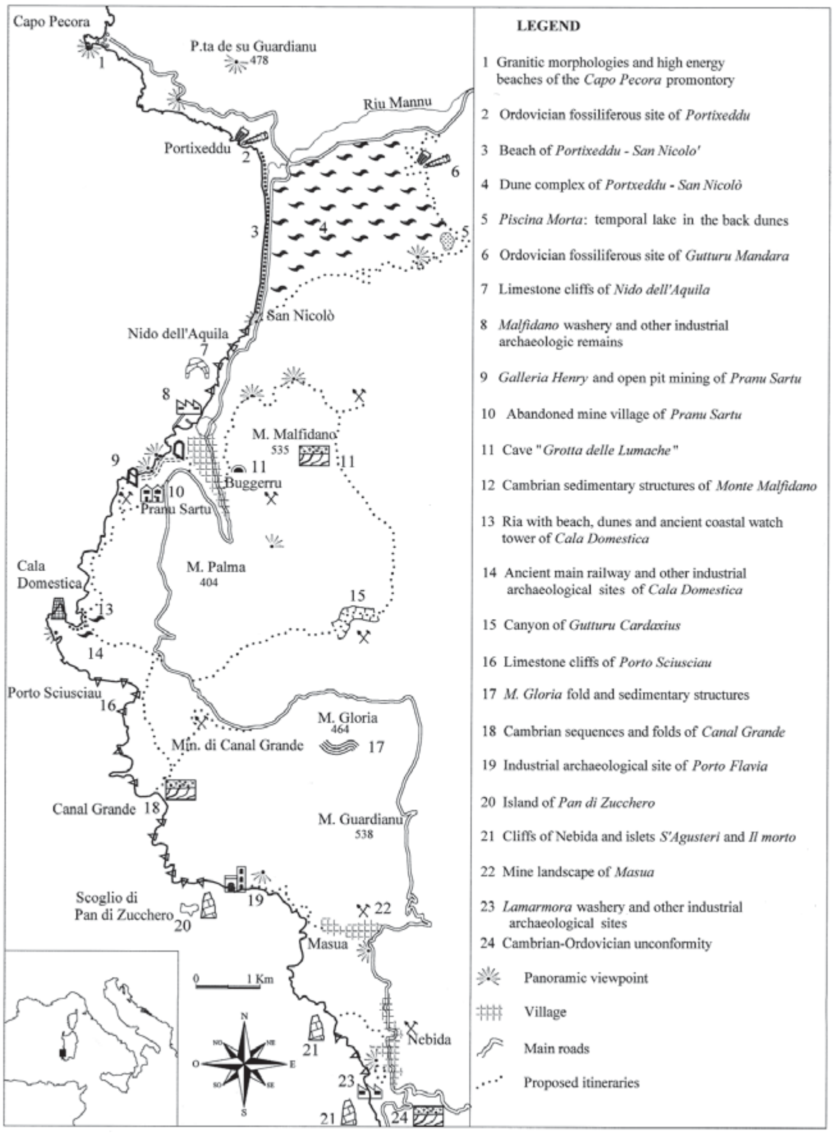

Fig. 2. Map of the geo-environmental characteristics, the coastal dynamics, the monitoring system and the accesses to the sea and beach.

view longitudinal, parabolic and transversal dunes can be distinguished. Since more than 40 yr this dune field has been stabilized through the plantation of many trees and shrubs. This makes this area very interesting; it has been classified as an ecotope of vegetational interest. The dunes are very rich in endemic plant species and one of the few places of Sardinia in which *Pinus pinea* and *Quercus coccifera* grow naturally (Mossa 1990).

The coast between Portixeddu and San Nicolò is characterized by an almost 3 km long beach fed by the Portixeddu dune field (App. 1). This is the most important beach of this area, and a major attraction for tourists during the summer season. The sands of the beach show a typical variation of psammophilic vegetation; on the embryonic dunes *Agropyron junceum* prevails, on the mobile dunes the *Ammophila littoralis*, and on the inner dunes the abundance of the endemic *Silene corsica* can be noted (Mossa 1990). From an entomological point of view the occurrence of the rare endemic beetle *Calinemis sardiniensis* should be stressed. In the past years geo-environmental monitoring enabled the analysis of the natural and human induced development of this beach. Only minor variation occurs and there is a satisfactory sedimentary balance (Cesaraccio et al. 1986; Di Gregorio et al. 1997; Arisci et al. 1999, 2001b).

Behind the extensive dune field lies Piscina Morta, a little natural temporary freshwater lake formed by the obstruction of some minor streamlets by eolian sand deposits. This marshy lake can completely dry out in the hot summer months. One flank of this lake is settled on grey-greenish Upper Ordovician fossiliferous slates upon which three different generations of eolian sands are deposited (Cesaraccio et al. 1986).

Between San Nicolò and the little town of Buggerru waxy limestone of the San Giovanni Formation (Gonnesa Group, Lower Cambrian) crops out for ca. 1.5 km. This coastal karst area, called Nido d'Aquila contains many small caves and some rock arches and karst pinnacles (Forti & Perna 1982; Barca & Di Gregorio 1999). In a cave at the northern part of the beach of Buggerru interesting Quaternary sediments and a fossil wave-notch can be seen. In the rocky vegetation of this area several endemic plants occur, notably *Limonium sulcitanum, Hyoseris taurina* and *Pancratium illyricum*. Furthermore, many seabirds such as *Calonectris diomedea, Puffinus yelkouan, Phalacrocorax aristotelis desmarestii, Falco peregrinus, Larus audouinii* and *L. cachinnans* occur in caves and niches, which makes this area an interesting faunistic site.

To the south of Nido d'Aquila, in a natural inlet, the mine town of Buggerru with its marina of the area is situated; it was founded by the owners of the Malfidano mine. The Malfidano Pb-Zn ore deposits have been exploited since Roman times, but the main industrial activity dates from 1870 until its closure in 1961. The washery of Malfidano, on the beach of Buggerru, has functioned until 1977 (Mezzolani & Simoncini 1993). At present this industrial archaeological site is being restored for tourist visits in the framework of the 'Geomining, Historical and Environmental Park of Sardinia'.

On the plateau immediately south of Buggerru the abandoned mine village of Pranu Sartu can be visited: this settlement is related to an oxidized Pb-Zn deposit and to the Malfidano mine company. This mineral deposit was discovered in 1867 and was exploited first for Pb and Zn, later also for Ag, until the early 1950s (Mezzolani & Simoncini 1993). In the near future the ruins of this village, on the border of a big open pit excavation can become a major tourist attraction of the area, together with the 'Galleria Henry', that carried the mineral by a subterranean railway, bordering the cliffs, to the Malfidano washery. This subterranean mine tunnel has already become a touristic and cultural attraction.

On the flank of Monte Malfidano above Buggerru some boys from the town discovered, only ca. 15 yr ago, the small entrance of the Grotta delle Lumache. The greatness of the cave has immediately led to the closure of the entrance by a fence to prevent the destruction of the beautiful concretions. It opens in the limestones of Lower Cambrian age. The rooms are characterized by great fossil columns, and the beauty of the cave has suggested its tourist exploitation from the beginning. At the end of the cave, close to the surface, the bony remains of a deer were discovered (De Waele & Grafitti 2000). Recently, a monitoring investigation has been performed to determine whether or not the cave will be opened to the public (Chiesi et al. 2001).

Along the road that leads from Buggerru to the abandoned Pb-Zn mine of Nanni Frau, on the northeastern slope of Monte Malfidano, the Lower Cambrian Punta Manna (Nebida Group) and Santa Barbara Formations (Gonnesa Group) crop out and show evident sedimentary stratification and slump structures. These represent the slope facies of these formations which have important educational value (Bechstadt & Boni 1996).

Some km south of Pranu Sartu Cala Domestica is encountered, constituting a natural inlet (*ria*) hosted in grey finely laminated dolomites of the Santa Barbara Formation (Gonnesa Group, Lower Cambrian) (Bechstadt & Boni 1996), characterized by two beautiful sandy beaches and a small dune field. On the walls of the natural channel of Riu Domestica fossil Pleistocene cross-bedded dune sediments are also present, related to late Quaternary sea level changes. On the promontories of this *ria* Mediterranean maquis with *Juniperus phoenicea* is found, while on the sandy deposits of the beach and of the dunes the typical psammophilic vegetation of *Agropyron junceum* and *Ammophila littoralis* has established. On the beach and along the valley many ruins of mine buildings and warehouses and old railway tracks are found – at Cala Domestica the Pb-Zn mineral was loaded on little boats that sailed from here to Carloforte on the Island of San Pietro (Barca & Di Gregorio 1999; Mezzolani & Simoncini 1993). On the southern promontory of Cala Domestica, an ancient Spanish coastal watch tower reminds us of the historical importance of this place to control the coastline and the arrival of barbarian pirates.

The small temporary river of Gutturu Cardaxius, responsible for the formation of Cala Domestica ria, cuts the metasandstones and metasiltites of the Nebida Group (Lower Cambrian) in its final part, characterized by a more or less wide valley. Upstream this river forms a narrow karstic canyon in the metadolostones and metalimestones of the Gonnesa Group (Lower Cambrian) with interesting karstic features, abandoned Pb-Zn mines, hydrothermal quartz veins and very beautiful slickensides.

Further south on the coast the semi-circular bay of Porto Sciusciau is situated in the grey dolomites of the Santa Barbara Formation. The dolomitic cliffs are eroded by the sea creating an interesting coastal landscape, ideal for the nesting of many seabird species. Along the fractures in the dolomites several karstic coastal caves have been formed (Barca & Di Gregorio 1999).

A little more southwards Canal Grande is found, representing a natural inlet which rocks are mainly constituted of metasandstones, phyllites of the Matoppa and Punta Manna Formations (Nebida Group, Lower Cambrian) followed laterally by dolomitic limestones of the Santa Barbara Formation (Gonnesa Group, Lower Cambrian). These rocks form the flank of a fold with strata inclined 60° towards the southeast. In the meta-sandstones, frequently decorated with beautiful ripple marks, a rich trilobite fauna has been reported and along the coastline nearby two beautiful natural rock arches in the phyllites can be observed (Barca & Di Gregorio 1999). Furthermore, many natural karstic caves have been explored in the dolomitic limestones, and among these the 'Grotta delle Spigole' can be mentioned (Forti & Perna 1982).

Some km to the south Porto Flavia is situated, directly above the sea in the 300m metres high limestone cliffs of Schina 'e Monte Nai (Fig. 3). This important site of industrial archaeology, composed of an artificial tunnel, several silos for the stocking of the minerals and a structure that enabled to carry the ships, was conceived by the engineer Cesare Vecelli and built in the 1920s to enable the shipping of minerals from the Masua and the Pranu Sartu mines (Mezzolani & Simoncini 1993). This place, of extraordinary touristic interest, has been opened to public very recently and is already frequently visited.

The small island of Pan di Zucchero is a great limestone block embedded in Ordovician red meta-siltstones, spared from marine erosion. It is composed of white waxy limestones of the Santa Barbara Formation (Gonnesa Group, Lower Cambrian) with yellow dolomite parts, these latter accompanying a minor silver-rich galena deposit that has been exploited in the past (App. 1). Two coastal erosion caves, formed along two main fractured zones, and the remains of a depression on top can easily be observed from the coast. The vegetation of this islet is the most authentic of all the Sardinian micro-insular habitats. The most abundant species is *Artemisia arborescens*, while *Bellium bellidioides, B. crassifolium, Brassica insularis, Hyoseris taurina, Limonium sulcitanum, Seseli bocconi* ssp. *praecox* and *Silene martinolii* are among the species of particular phytogeographic interest (Bocchieri 1990).

On the coast near Masua and below Nebida the sea is characterized by the presence of other small islands composed of white Lower Cambrian waxy limestone embedded in violet red conglomerates of the Ordovician. These white sea cliffs, together with the Pan di Zucchero island, the red coast, the blue sea and the many abandoned mine remains form a landscape which is unique for the Mediterranean.

The Masua mine was opened in 1859 for the exploitation of Pb and Zn minerals and was one of the last mines to be closed in the early 1990s. The minerals were transported by a railway to the underground tunnel of Porto Flavia, where they were directly shipped. To enable the exploitation of the ore deposits underneath the sea level this mine had a pumping system that functioned until 1991. Today the interest of this mine is not only related to industrial archaeology, but also to its sedimentary structures, karstic phenomena and natural and human landscape.

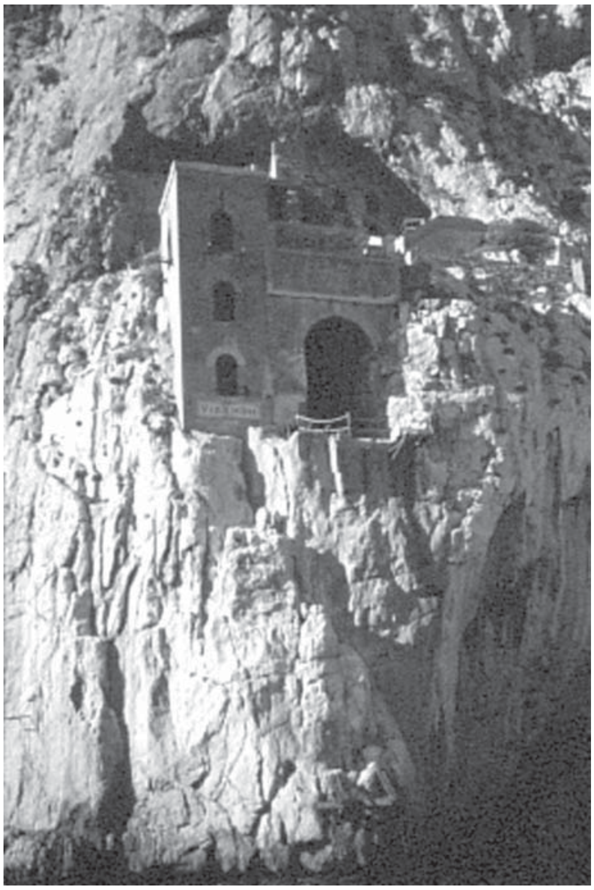

Fig. 3. The archaeological mine site of Porto Flavia, a subterranean tunnel constructed in 1924, ending at 36 m height on a limestone cliff above the sea, enabling to load the ships with Pb-Zn minerals exploited in the Masua mine, reducing in this way shipping expenses significantly.

At Nebida another Pb-Zn mine was active since 1865 until the late 1980s, and from these mining activities the washery of Lamarmora is the most remarkable remainder, situated on the rocky coast below the little town (Fig. 4). This treatment plant is constructed on the Ordovician red phyllites and metasiltstones, containing big fragments of Cambrian limestones.

Along the panoramic walk-way of Nebida, above the Lamarmora washery, and on the side of the main road to the south of the town, another intersting geosite can be very clearly observed. In fact, during Ordovician times the marine deposits were shortly exposed to an erosional continental phase (*'Fase Sarda'*) that created an angular unconformity between weakly folded and faulted Upper Cambrian and Lower Ordovician (Tremadoc) sediments and the younger Ordovician strata composed of conglomerates, with very big Cambrian limestone fragments at the basis with an overall reddish colour (Bechstadt & Boni 1996).

Some examples of geo-environmental monitoring

In order to assess the environmental impact on the natural and geological monuments, and especially on those where tourist pressure and impact is greatest (e.g. coastal landscapes, beaches, dunes and subterranean environments) several monitoring projects have been performed in the study area. Among these the most interesting are the monitoring campaigns organized for the Portixeddu beach in the past four years (Arisci et al. 2001a) and the ones co-ordinated by the Italian Speleological Society in the Grotta delle Lumache (Chiesi et al. 2001).

Study of the Portixeddu-San Nicolò beach

To evaluate the carrying capacity of the Portixeddu beach several geological-geomorphological (morphological information, coastal dynamics, grain size of the sediments, etc.) and environmental parameters (presence of dunes, vegetation, artificial structures such as parking places, accesses to the beach, houses, marinas etc.) have been measured and monitored for more than two years and these data have been synthesized in a thematic map (Fig. 5). Besides the graphical representation of all these aspects, the variation of the coastline has also been summarized, comparing cartographic data in scale 1:10,000 (relative to the years 1978 and 1997) and the data of a recent topographic campaign performed in the years 1999 and 2000 using Topcon GTS-3B. Furthermore we have also confronted our data with the measurements performed by other authors in the years 1980, 1983 and 1984 (Cesaraccio et al. 1986) (Table 1). In the campaigns of 1999-2000, 27 sections have been monitored for a total number of 231 measurements taken from two fixed stations at Portixeddu and at San Nicolò in the year 1999 and 159 measurements from the same stations in the 2000 campaign. These surveying and sampling campaigns are still going on along the sections that have been constructed up to a bathymetric depth of –20 m to reconstruct the tridimensional form of the sedimentary unit. From all these data emerges that during the past 22 yr the northern part of the beach (sections T1 to T11) has retreated for about 20 - 25 m, the central sector (T12-T15) is substantially stable, the southern-central part (T16-T21) has retreated visibly (between 10 and 30 m) while the most southern beach (T21-T27) is relatively stable.

Fig. 4. On the steep coast underneath the town of Nebida the Lamarmora washery is situated, which treated the minerals of the Nebida mine. It represents one of the most interesting mine-archaeological sites of this part of the coast.

On the other hand, considering only the past four years (1997-2000), using the relatively accurate 1997 cartographic data of the 1 : 10 000 map, the northern and central-southern parts of the beach appear in clear regression (excluding the Riu Mannu river mouth) while the central-northern and the most southern sectors show accretion. This development, based on the more precise 1997 cartographic data, has been summarized in the histograms aside the beach in Fig. 5 and in the last column of Table 1.

The Riu Mannu river mouth is extremely variable in time, depending both on coastal dynamics and on river flow rate, pointing northwards or southwards and changing its course for even more than 100 m.

Many beach sediment samples have been taken and analysed and the results have been summarized in the thematic map. The majority of the samples belong to the medium sized sands with ϕ intervals between 1 and 2 (0.50 and 0.25 mm, respectively), sometimes accompanied with rounded pebbles representing the lithology of the area (phyllites, granites, metalimestones and metadolomites). More than 90 % of the sediment is composed of rounded quartz grains, proving advanced maturity, and grains become less rounded in the landward samples. Several samples of sediment of the beach, the proximal dunes and the inland stabilized dunes have been successively analysed by SEM to observe micromorphologies. The beach sands are characterized by pitting phenomena due to continuous impacts caused by wave motion and enlarged by salt water dissolution especially along the microfractures, while the more stabilized dune sands show increasing phenomena of pedogenesis such as precipitation of carbonatic cement and reprecipitation of silica.

In order to calculate the carrying capacity of the beach, the type of access to the sea (natural or cemented, stairs, paths, etc.) has been determined, the surface which is used and its relative length has been calculated;

furthermore the grain size of the sediments composing it, the slope of the submerged beach at – 5 m and the evolutionary tendency (advancing, eroding or stable) have been analysed. In this way 24 different segments of beach have been distinguished representing in total a beach surface of 105546 m^2 over a length of 2560 m.

The slope of the submerged beach, important for the evaluation of possible dangers for bathing, varies considerably in relation with the affecting energy flux (Atzeni et al. 2001), ranging from 1.0 % on the northern and southern part to 5.5 % in the central portion of the beach, suggesting more caution for frequentation in this last sector.

The evaluation of the carrying capacity coefficient for this beach has been performed using two methods (Table 2). The first is suggested in the Regional Directive no. 5D (Am-Ma) of 20.03.1978; it allows two visitors on every m of beach length if its width is ≥ 50 m, and only one visitor/m for narrower beaches. This amounts to 3079 visitors on the Portixeddu beach. However, the method, which seems to take care of the environment, assumes a regular distribution of bathers over the beach, without taking into account the irregular occurrence of young dunes with their vulnerable vegetation which would need precautions.

The second method has been suggested by a recent research (Arisci et al. 2000) and takes into account a series of parameters that influence both the environmental quality (geomorphology, habitat, flora and fauna, landscape etc.) and the environmental sensibility (grain size, wave energy, parking places and access to the beach, evolution pattern, slope of the submerged beach etc.) of the beach segments. To every parameter a value from 1 to 3 is assigned (e.g. grain size influences the sensibility of the beach segment to erosion meaning that the coarser the sediment the lower the value will be). The sum of these values is a marker of how sensible each beach segment is: for beach areas with high values (thus more sensible) small numbers of bathers should be allowed while less sensible areas

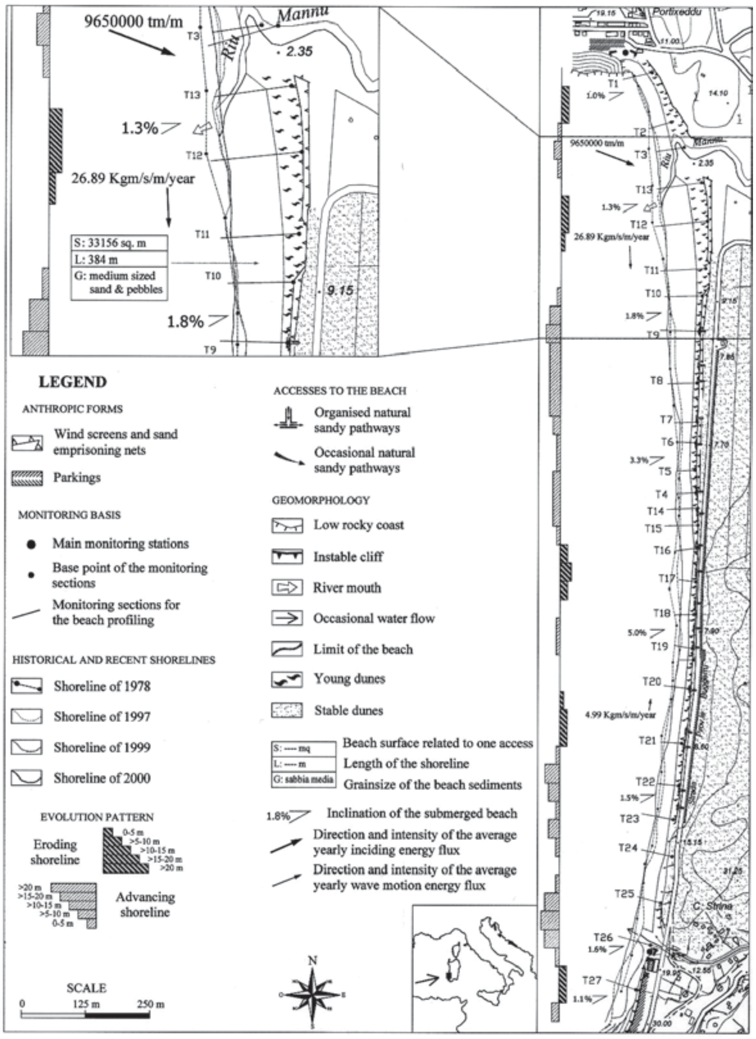

Fig. 5. Map of the geo-environmental characteristics, the coastal dynamics, the monitoring system and the accesses to the sea and beach.

(with low values) can carry more visitors. Therefore the environmental sensibility coefficient for each beach segment has been defined, expressed in visitors/m^2 of beach. For beach segments with high environmental quality and high environmental sensibility, thus with high values, one bather on every 40 m^2 of beach should be sustainable. For less sensible areas this number grows to one visitor/20 m^2 while for the beach segments with the lowest values as much as one visitor/10 m^2 is believed to be sustainable.

Once this parameter has been defined the sustainable quantity of visitors can easily be obtained multiplying the environmental sensibility coefficient with the surface of the beach segment, arriving for the entire Portixeddu beach at a number of 5634 visitors, sensibly more than those obtained using the regional directive. This higher number of visitors will, according to the authors, still be sustainable for the beach, but should be periodically controlled in order to take into account the environmental feedback of the entire system.

Grotta delle Lumache

This little cave, discovered in 1988, opens in limestones of Lower Cambrian age and is composed of some big rooms well decorated with great fossil columns and many calcite concretions. In the final part, close to the surface, the bony remains of a deer have been discovered. Recently, during a biospeleologic campaign, some interesting cave dwelling animals have been observed and are currently studied (De Waele & Grafitti 2000).

Table 1. Comparison between widths (distance between the base point of the section and shoreline) deduced from maps at scale 1 : 10 000 (1978 and 1997) and measured during the topographical campaigns of 1999 and 2000 and general beach development (Beach): A = advancing; S = stable; E = erosive.

Section No.	Width (m) 1978	Width (m) 1997	Width (m) 1999	Width (m) 2000	Beach 1997-2000
1	49	49	65	53	E
2	64	53	51	55	S
3	96	68	64	77	A
13	135	114	122	114	S
12	148	123	121	118	E
11	112	108	113	107	S
10	94	90	88	92	S
9	79	66	65	87	A
8	70	53	54	68	A
7	60	42	58	48	A
6	51	37	55	44	A
5	46	41	43	50	A
4	46	40	42	52	A
14	52	48	49	61	A
15	55	48	43	55	A
16	60	51	21	46	E
17	69	51	31	38	E
18	53	38	38	37	S
19	49	32	27	37	A
20	46	40	37	39	S
21	58	47	41	36	E
22	59	40	31	58	A
23	46	42	46	49	A
24	62	52	55	68	A
25	56	49	45	58	A
26	46	38	52	57	A
27	37	60	46	49	E

The subterranean environment of caves is intrinsically very vulnerable to open air environments, and therefore, before opening such places to the public, a monitoring project is very much recommended if not essential to guarantee a long-during and sustainable economical activity. For this reason the Grotta delle Lumache has been monitored for an entire year (from 18 March 2000 to 17 March 2001) (Chiesi et al. 2002) controlling external rainfall, temperature and relative humidity and internal temperature, relative humidity, carbondioxide and radon (Fig. 6). During this controlled period the human frequentation has been accurately monitored to be able to correlate these occasional visits with the changes in cave microclimate.

The monitoring data have pointed out that the cave, that has two opposite entrances with a difference in altitude of ca. 15 m, acts as a 'trap of cold' in normal conditions: in fact, both monitoring internal temperature sensors stay below the mean annual outside temperature of 17.1 °C for almost all the time (only sensor A detects higher temperatures for a few days per year) (App. 2). This is reasonable knowing that the main chambers are situated below both entrances, which are in turn very small relative to the total cave volume. Sporadically though, when air pressure is unstable outside (e.g. windy days) an air flow inside the cave can develop between the two entrances (barometric cave), but measures have shown that air velocity inside the chambers is normally very low (between 0.1 and 0.3 m/s). In general the cave has only small energy fluxes (scarce air flow, thermal inertia, relative humidity of air constantly close to 100 % even during long periods of drought, low infiltration of water and seepage, slow exchanges of air and CO_2, etc.) and can be classified as a 'low energy cave', thus defining a relatively sensible and vulnerable environment.

For this reason a low visitor regime combined with a constant monitoring of the geo-environmental parameters (CO_2 and temperature of the cave air) is recommended in order to preserve the cave environment and also to allow a more precise determination of the carrying capacity. Chiesi et al. (2002) proposed a scientific-didactic use of the cave on three days per week and a daily visitor flux of less than 50 persons (divided into two groups) that could stay for about two hours underground. This type of visits, directed towards schools and cultural associations, could be applied from October to May, while during the four summer months the cave could be open every day holding the 2 × 25 persons/day limit as explained above. The global tourist flux should be about 8000 visitors/yr and probably would not compromise the delicate cave environment.

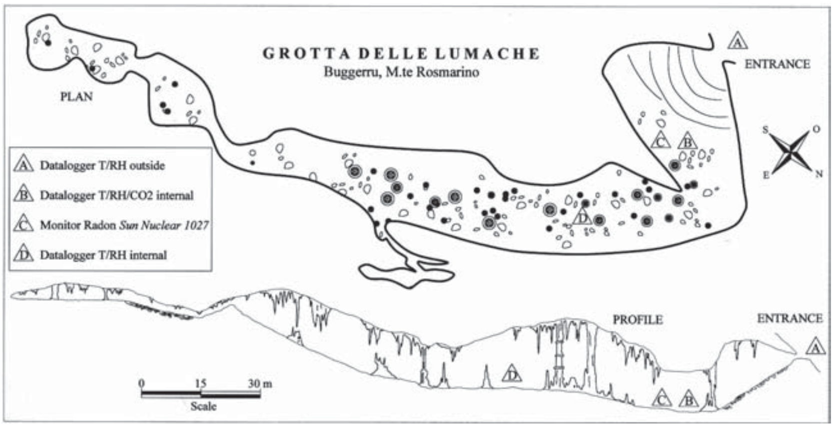

Fig. 6. Section of the Cave 'Grotta delle Lumache' with the monitoring stations (from Naseddu et al. 1997).

Sustainable coastal touristic development

The coastal area from Capo Pecora to Nebida, until recently exploited for its mineral deposits, has a considerable chance of becoming an attractive touristic centre. Recently, many of the geosites and archaeological-industrial mine localities have been restored in order to attract tourists, but much work is still necessary.

Many sites described above have been classified, the first five as a 'Site of Communitarian Interest' according to the CEE directive 92/43 'Habitat'.

ITB000030 - Capo Pecora;
ITB002249 - Is Compinxius-Campo Dunale di Buggerru-Portixeddu;
ITB002247 - San Nicolò-dune di Portixeddu-Buggerru;
ITB002248 - Dune di Portixeddu-Buggerru-San Nicolò-Piscina Morta;
ITB000029 - Costa di Nebida
Natural Monument: Pan di Zucchero
Natural Regional Reserve: Costa di Nebida and Capo Pecora.

Other areas have been protected by Forestry Laws or Local Territorial Plans.

Among the most important actions to be taken we mention the establishment of three local visitor centres at Portixeddu, Buggerru and Masua, the layout of several thematic trekking routes and the installation of local explanation panels and guide-books, to inform tourists about the natural values, geology, geomorphology and history (especially regarding the mines). Another important aspect to develop is related to hosting facilities: hotels, renting rooms, restaurants etc.

Special care has to be taken for the beach and the dunes of Portixeddu-San Nicolò through increasing facilities and safety while avoiding the destruction of the young dunes and its typical vegetation.

Table 2. Evaluation of the Carrying Capacity Coefficient (CCC) – using the Regional Directive no. 5D (Am-Ma) of 20.03.1978 and the Environmental Sensibility Coefficient (ESC; visitors/m^2 beach) proposed by Arisci et al. (2000). Also given Mean beach width during 1999-2000 (m) and total number of visitors allowed ($Visitors_{tot}$)

Sector	Length (m)	Width (m)	Surface (m^2)	CCC	$Visitor_{tot}$	ESC	$Visitor_{tot}$
1	359	37	13778	1	359	0.05	689
2	384	81	33156	2	768	0.025	829
3	62	60	3167	2	124	0.1	317
4	73	50	2963	2	146	0.1	296
5	82	42	2441	1	82	0.1	244
6	106	31	2559	1	106	0.1	256
7	95	35	2758	1	95	0.1	276
8	68	38	2283	1	68	0.1	228
9	83	26	3080	1	83	0.05	154
10	77	22	3089	1	77	0.025	77
11	78	23	2255	1	78	0.05	113
12	60	22	1327	1	60	0.025	33
13	87	23	2037	1	87	0.025	51
14	112	28	3412	1	112	0.05	170
15	69	31	2547	1	69	0.05	127
16	83	29	2914	1	83	0.05	146
17	86	33	2584	1	86	0.05	129
18	67	37	2064	1	67	0.1	206
19	83	39	2518	1	83	0.1	252
20	73	36	2554	1	73	0.1	255
21	57	34	2029	1	57	0.1	203
22	51	38	1632	1	51	0.1	163
23	35	43	1024	1	35	0.05	51
24	230	26	7375	1	230	0.05	369
Total	2560		105546		3079		5634

Conclusions

The SW coast of Sardinia is considered one of the most interesting coastal areas and landscapes of Sardinia. Since the closure of the mines 20 yr ago the main local income is from tourism related to the industrial-archaeological remains, together with many geological, natural and cultural monuments and to the importance and variety of the coastal landscape. The integrated model of sustainable development of this exceptional coastal landscape, proposed in this paper, is based on several thematic maps, including those for geology, geomorphology, land cover and land-use, industrial archaeology, and land evaluation. In accordance with this model several actions have been proposed:

- The establishment of a natural reserve with specific geological and geomorphologic sites;
- The creation of several touristic circuits which may form the basis for a further valorization of this territory;
- The selection of areas where it is possible to establish tourist settlements which are compatible with conservation of the natural environment.

Acknowledgements. This research forms part of the National Project 'Analysis of the sedimentological and morphological variation of beaches caused by protection interventions on coastal areas' (Head of the Operative Unit: Prof. Felice Di Gregorio). The model presented has been proposed in the framework of an INTERREG II C program: 'Modelos Territoriales sostenibiles para los espacios litorales mediterraneos'. We thank an anonymous reviewer for useful comments which have improved the quality of this paper.

References

Arisci, A., Di Gregorio, F. & Fanni, M. 1999. Dinamica costiera e rischio ambientale nel litorale tra Portixeddu e Buggerru (Sardegna SW). In: *Atti della 3. Conferenza ASITA 1999*, pp. 145-152. ASITA, Napoli, IT.

Arisci, A., De Waele, J., Di Gregorio, F. 2000. Natural and scientific valence of the Gulf of Orosei Coast (Central-East Sardinia) and its carrying capacity with particular regard to the pocket-beaches. *Period. Biol.* 102, Suppl. 1: 595-603.

Arisci, A., De Waele, J., Di Gregorio, F., Ferrucci, I. & Follesa, R. 2001a. Geosites and touristic development of the karstic coastline of Southwest Sardinia. In: Özhan, E. (ed.) *Medcoast 01: Proceedings of the 5th International Conference on the Mediterranean Coastal Environment, 23-27 October 2001, Hammamet, Tunisia*, Vol. 1, pp. 302-314. Middle East Technical University, Ankara, TR.

Arisci, A., De Waele, J., Di Gregorio, F., Ferrucci, I., Follesa, R. 2001b. Proposta per la gestione sostenibile della fascia costiera tra Portixeddu e San Nicolò (Buggerru-Fluminimaggiore). In: *Modelli territoriali sostenibili per gli spazi litoranei del mediterraneo, Regione Autonoma della Sardegna, Assessorato agli Enti Locali, Finanze ed Urbanistica*, pp. 45-64. Regione Autonoma della Sardegna, Cagliari, IT.

Atzeni, A., DeMuro, S., Di Gregorio, F. & Piras, G. 2001. *Carta del rischio ambientale nelle coste della Sardegna, scala 1:250.000*. SELCA, Firenze, IT.

Barca, S. & Di Gregorio, F. 1999. *Paesaggi e monumenti geologici della provincia di Cagliari*. Saredit, Cagliari.

Bechstadt, T. & Boni, M. 1996. *Sedimentological, stratigraphical and ore deposits field guide of the autochtonous Cambro-Ordovician of Southwestern Sardinia*. Memorie descrittive della Carta Geologica d'Italia 48, Roma, IT.

Bocchieri, E. 1990. Some herborizations on the islet of Pan di Zucchero (Sardinia W-SW) *Giorn Bot. Ital.* 124: 615-621.

Cesaraccio, M., Puxeddu, C. & Ulzega, A. 1986. Geomorfologia della fascia costiera tra Buggerru e Portixeddu nella Sardegna sud-occidentale. *Rend. Sem. Fac. Sc. Univ. Cagliari* 561: 75-88.

Chiesi, M., Cigna, A.A., Fadda, A., Fancello, L., Forti, P., Grafitti, G., Murgia, F., Naseddu, A. & Perna, G. 2002. La grotta delle Lumache di Buggerru: risultati preliminari del monitoraggio ambientale e delle ricerche scientifiche finalizzati alla definizione del livello di fruibilità compatibile. In: De Waele, J. (ed.) *Atti del Convegno di Studio Il Carsismo e la Ricerca speleologica in Sardegna, Cagliari 23-25 novembre 2001*, Anthèo 6, pp. 125-142.

Civita, M., Cocozza, T., Forti, P., Perna, G. & Turi, B. 1983. Idrogeologia del bacino minerario dell'Iglesiente (Sardegna sud occidentale). *Mem. Ist. Ital. Spel.* 2(2): 1-137.

De Waele, J. & Grafitti, G. 2000. Show caves in Sardinia: geologic and biologic aspects. In: Cigna, A.A. (ed.) *Proceedings III. Congress ISCA: Show caves: where, how, why. Santadi, 19-25 Ottobre 1998*, pp. 77-91. ISCA, Gagliari, IT.

Di Gregorio, F., Ferrara, C. & Ibba, A. 1997. *Atlante delle spiagge Italiane, Fogli n° 224, Capo Pecora e n°225, Guspini*. SELCA, Firenze, IT.

Forti, P. & Perna, G. 1982. Le cavità naturali dell'Iglesiente. *Mem. Ist. Ital. Spel.* 2(1): 1-229.

Leone, F., Hamman, W., Laske, R., Serpagli, E. & Villas, E. 1991. Lithostratigraphic units and biostratigraphy of the post-sardic Ordovician sequence in south-west Sardinia. *Boll. Soc. Paleont. Ital.* 30(2): 201-235.

Mezzolani, S., Simoncini, A. 1993. *Paesaggi e architetture delle miniere*. Archivio Fotografico Sardo Editrice, Nuoro, IT.

Mossa, L. 1990. La vegetazione forestale del Campo dunale di Buggerru-Portixeddu (Sardegna occidentale) *Analisi di Botanica, Studi sul territorio*, Vol. 43, Suppl. 7, 1990.

Naseddu A., Papinuto S., Fadda A. 1997. La grotta delle Lumache di Buggerru. *Speleologia* 37: 49-54.

Pillola, G.L. 1989. Trilobites du Cambrien inférieur du SW de la Sardaigne, Italie. *Paleontogr. Ital.* 78: 1-174.

Received 29 August 2002;
Revision received 18 April 2003;
Accepted 18 April 2003.
Co-ordinating Editors M. Cassar & E. van der Maarel.

For Apps. 1 and 2, see JCC Electronic Archives; www.opuluspress.se/pub/archives/index.htm