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PALEOENVIRONMENTS RECONSTRUCTED FROM THE ANALYSES OF LOESS SEQUENCES ON SUSAK ISLAND, ADRIATIC SEA

ÉVA KIS[1], FERENC SCHWEITZER[1], DÉNES LÓCZY[2]

[1]Geographical Research Institute, Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, Budapest, Hungary
[2]Institute of Geography, University of Pécs, Hungary
E-mail: eva.kis@csfk.mta.hu

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Abstract
Susak Island is the outermost member of the archipelago of the Kvarner Bay, North Adriatic Sea, Croatia. Its long-term landscape evolution is defined by tectonic movements. Most characteristic are partly exhumed landforms of an ancient terrane (scarps, uplifted limestone cliffs) in a still active neotectonic environment, but the most appropriate tools for the reconstruction of Quaternary paleoenvironments are loess and loess-like deposits. The Quaternary sequence is up to almost 100 m thickness locally and intensively studied by numerous disciplines (from structural geology to geochemistry and geomorphology) today. The special location of the island makes it a key area of research into the evolution of the broader environment, including the Po Plain as well as other Italian source areas of wind-borne and redeposited dust. The loess mantle was also of great importance for a paleoecological reconstruction of floral and faunal evolution, on which efforts of nature conservation are founded.

Keywords: loess-paleosol sequence, geomorphic evolution, paleoecology, Adriatic Sea

1. Introduction

Susak Island of 3.76 km^2 area, one of the members of the Kvarner Archipelago, occupies a key position in the northern section of the basin of the Adriatic Sea (Fig. 1, Photo 1) (Wein 1977). Along with the neighbouring islands it used to be part of the mainland and was detached from what is now the Dalmatian coast during postglacial marine transgressions. Its surface is constituted by a Mesozoic karst plateau which rises 98 m above the sea level and has very gentle (0-5º) slopes (Photo 2, Photo 3). The karst plateau of Susak is, in many respects, analogous to the karst of the Istrian peninsula.

Tectonically, Susak is part of the para-autochton of the Outer Dinarides. The island is located in a transitional zone of NW to SE strike and imbricate structure, at ca 6 km distance from a primary lineament between the Adriatic microplate and the Istrian platform (Bognar 2001). There is seismological evidence (the location of earthquake hypocentres) that the Adriatic microplate subducts under the Dinarides along the Cres – Unije – Susak – Dugi otok – Kornati fault zone. A consequence of this tectonic situation is the heavy dismembering of Susak and the neigbouring islands by secondary faultlines into small blocks. On the basis of recent studies on the neotectonics and geomorphology of the islands (Mihljevič 1995), it is assumed that a kinematic mechanism activated in recent times by a shift of stress from NE–SW direction to

Fig. 1. Location and topography of Susak Island

Photo 1. The loess island of Susak with view upon Mali Losinj (Photo by É. Kis)

N–S direction has deformed the orographic structure of the island and induced a retrograde rotation which is manifest in an arched convex topographic configuration. Neotectonic uplift more intensively affected the southwestern part of the island, while in the northeast the loess mantle is thicker.

The present geomorphology of the island, however, is mostly due to the accumulation and subsequent denudation of a deep loess mantle. The distinction between northern Mediterranean and North-African loess accumulations is generally accepted: the former refer to a periglacial environment, while the latter are of desert origin and date to pluvial intervals (Coudé-Gaussen 1991). The Mediterranean loess sequences in the Pre-Alpine and Adriatic region were studied in detail by Cremaschi (1987, Cremaschi et al. 2015). He also mapped the distribution of loess deposits typified according to their position in northern Italy (Fig. 2). In his typology, the loess on Susak falls into the class of loess deposited on karst plateaus.

Further geological (mineralogical, geochemical) and geomorphological studies on the island were performed by Bognár (1979), Bognár et al. (2002), Lužar-Oberriter et al. (2008), Mikulčić-Pavlaković et al. (2011), Wacha et al. (2011) and a monograph was published by the Geographical Research Institute, Hungarian Academy of Sciences (Bognár et al. 2003). The major findings of recent research can be summarised in the following:

- red clay with spherules (Photo 4, Photo

Photo 2. The higher (60-98 m) and the lower (30-50-m) geomorphological surfaces of Susak Island (Photo by É. Kis)

Photo 3. The uplifted southern part of the island (Photo by É. Kis)

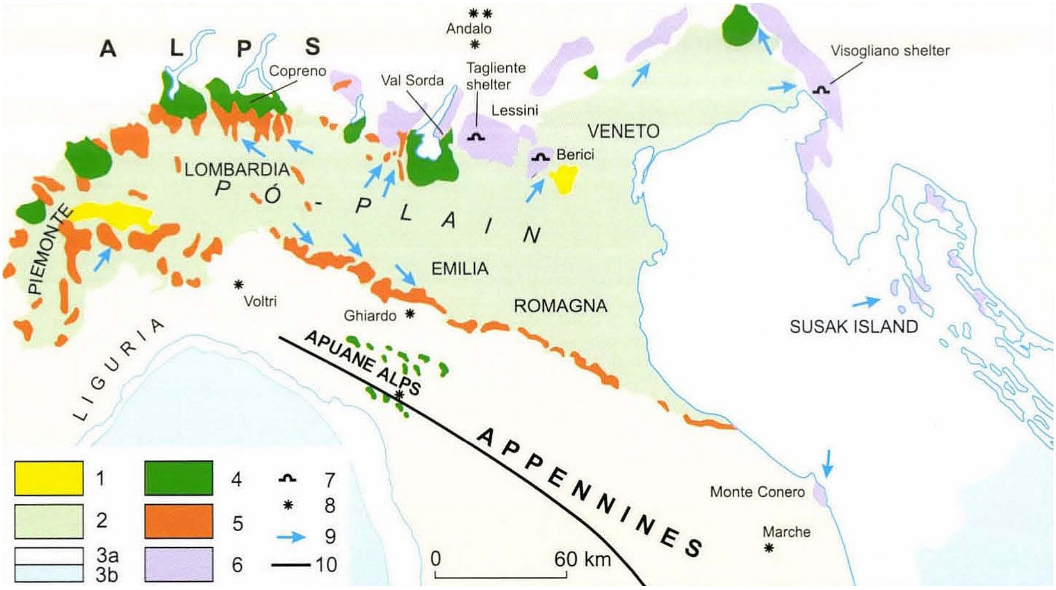

Fig. 2. Loess distribution in the North-Adriatic region (Chremaschi 1987b modified by Cremaschi 1991) – 1 = Pre-Quaternary rocks; 2 = Late Pleistocene and Holocene alluvial plain; 3 = present day sea extent with depth: 3a 0-100 m; 3b>100 m; 4 = Pre-Alpine and Appennine moraine system; 5 = loess deposits on fluviatile, fluvioglacial terraces and moraine ridges; 6 = loess deposits on karstic plateaus; 7 = loess in caves or shelters; 8 = loess on erosional surfaces; 9 = directions of dominant winds during loess sedimentation; 10 = possible south-west boundary of loess sedimentation during Upper Pleistocene

5) in the cracks of Cretaceous rudist limestone is dated 4–3 Ma old, it is a weathering product of subtropical karstification (Csarnotánum), retained in ruins, destroyed by interglacial transgressions and glacial action, when sea level was 100 m lower;

- the overlying reddish clay probably deposited between 3 – 1.8 Ma (Villányian – Villafranchian);
- sandy silts, sandstone with pisolites, sandy loess varieties and sands are of Middle to Late Pleistocene age (floodplains, alluvial fans);
- paleosols in the loess sequence point to warm and humid intervals, while the occurrence of sandy deposits refer to warm and dry phases;
- micromineralogical investigations reveal similarities between the heavy metal spectra of sediments on Susak and in the Po Plain, which suggest a common origin;
- the carbonate contents of these sediments, however, are quite different.

The above research findings have motivated the present authors to launch sedimentological, geochemical, geochronological and geomorphological investigations (relying on previous similar studies in Hungary and Central Europe – Pécsi and Richter 1996) with the purpose to reconstruct plaeoenvironments on the fascinating small island of Susak.

2. Methods

New approaches are applied to the study of loess-paleosol sequences as terrestrial archives of changes in the Pleistocene environment. The methods equally reveal the dynamics of sedimentation and allow vertical and horizontal correlations in the sequence.

In the centre of the sedimentological investigations stood the granulometric analyses of loess horizons at several typical sites on the island. New methods of environmental analysis were applied to draw precise conclusions from sediments

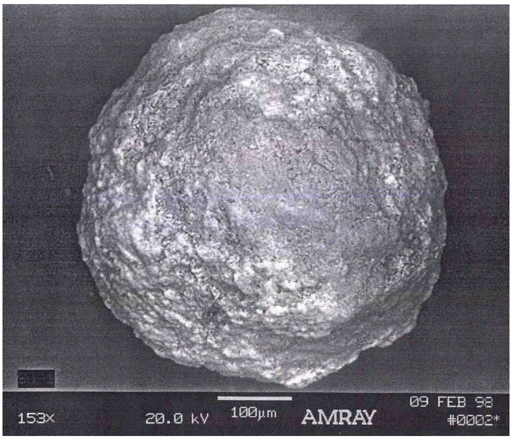

Photo 4. Spherule embedded in red clay (Photo by Gy. Szöőr)

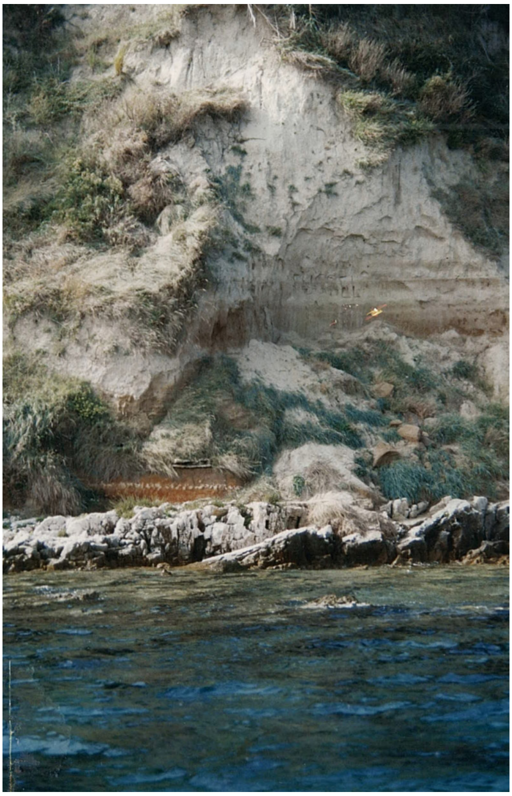
Photo 5. Loess-paleosol sequence in the north of the island (Photo by É. Kis)

to paleoenvironmental changes (Kis et al. 2011). The new parameters introduced in Hungary by authors, fineness (Fg) and weathering index (Kd) were studied jointly with traditional granulometric indicators, sorting (So), kurtosis (K), asymmetry (Sk), median values (Md), carbonate content and percentage grain size distribution.

Mineralogical and geochemical data were obtained by thermoanalytical and X-ray diffraction methods, calcimetric, stable isotope analyses and SEM-EDAX examinations (Szöőr 2003; Mikulčić-Pavlaković et al. 2011). As a result of mineralogical analyses several sand and tephra layers could also be described from the loess sequence. The chronological boundaries in the loess sequence were established through paleomagnetic and susceptibility studies (Schweitzer and Kis 2016; Wacha et al. 2011), supplemented with the interpretation of malacological and archaeological data. Relative dating was promoted by comparisons with the loess-paleosol sequences in the Carpathian Basin and absolute dates were obtained by radiocarbon dating.

Extensive geomorphological field work covered field surveys of landforms and geomorphometric measurements. Landforms were typified according to the intensity of processes of loess corrosion (gullying and piping) as well as marine abrasion and mass movements. Geomorphological mapping was applied to reveal the distribution of tectonic, accumulational (Photo 6), erosional, coastal, karst and man-made landforms. Through the genetic interpretation of the different members of the loess sequence past geomorphic processes which operated under different climatic conditions could also be reconstructed.

3. Results and discussion

Stratigraphy of loess on Susak Island

The granulometric and carbonate content analyses resulted in a generalised profile of loess on Susak (Fig. 5, Fig. 7). In loess stratigraphy altogether 31 horizons could be identified:

- 11 horizons of loess and 2 horizons of loess-like deposits;
- 11 layers of different paleosols (reddish,

Photo 6. Loess and loess-like deposits filling a dell on Susak (Photo by É. Kis)

Photo 7. Rotational landslide generated a complex assemblage of landforms in the southeastern part of the island (Photo by F. Schweitzer)

reddish brown, dark chocolate brown and slightly humic);

- 4 layers of coarse or fine sand;
- 3 tephra layers (reddish brown, yellow and grey).

Along a horizontal line at a given depth of the exposure the values of all sedimentological indicators can be read (Fig. 5). The boundaries of layers can be precisely identified (from the values of F_g, K_d és K), the fineness of deposits (Fg), warming maxima in soils and cooling minima in loess horizons. Sedimentation gaps are indicated by highly irregular values, which point to grains remained from eroded layers (Kd). Transportation conditions (So) and redeposition or in situ formation of layers (Sk) are also shown. When evaluating results for median grain diameter (Md) it was found that the Fg curves (next in the Figure) provide much more precise data. Therefore, we prefer the analysis of Fg values. In the profile the Last Interglacial series is almost uninterrupted.

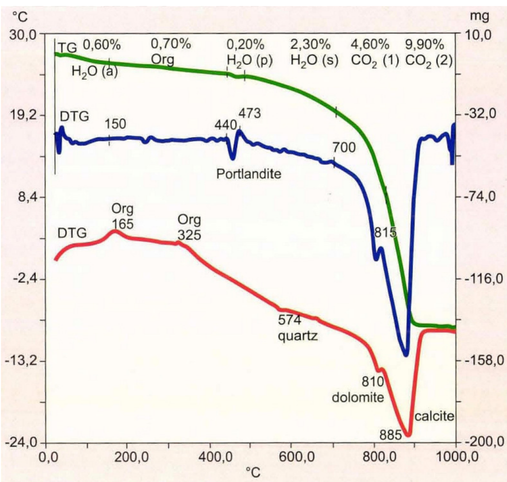

Fig. 3. Thermoanalytical courve of young loess from the upper part of the Susak profile (Szőőr Gy.) – X-ray analysis defined the following minerals:illite-mont- morillonite 1%, muscovite, 9%, chlorite 7%, quartz 30%, plagioclase feldspar 11%, calcite 25%, dolomite 15%, amorphous 2%

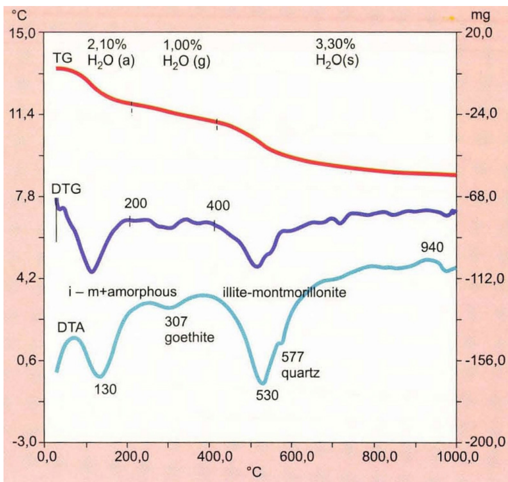

Fig. 4. Thermoanalytical courve of old loess from Susak (Szőőr Gy.) – X-ray analysis defined the following minerals: montmorillonite 2%, illite-montmorillonite 4%, illite 14%, chlorite 3%, quartz 42%, plagi- oclase feldspar 15%, K- feld-spar 4%, calcite 3%, pyrite 2%, amorphous 6%

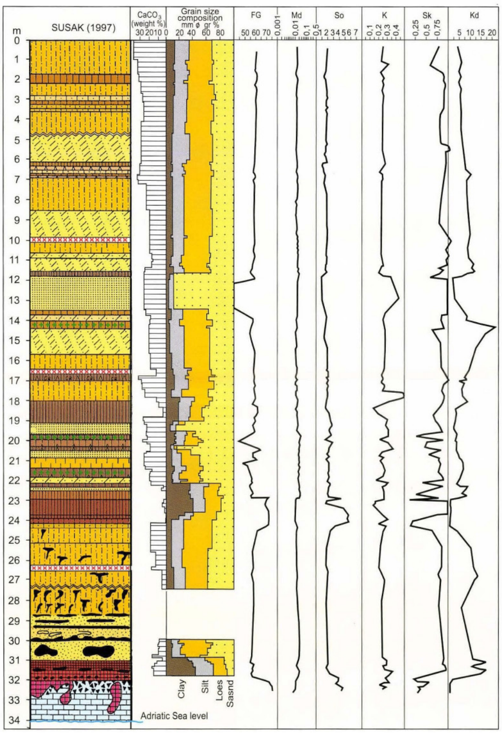

Fig. 5. Loess profile from Susak. (Stratigraphical analysis by Schweitzer F., Kis É., Bognar A., Balogh J., di Gleria M.) Granulometric parameter values (Kis, É., Schweitzer F., di Gleria M., Balogh J.)

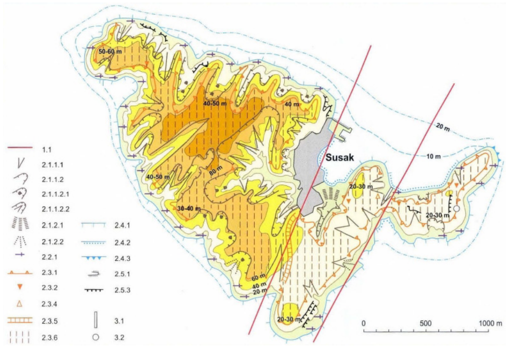

Fig. 6. Geomorphological map of Susak Island (Bognár, A) – 1 = Endogeneous relief; 1.1. = faults; 2 = Exogeneous relief; 2.1. = Slope landforms; 2.1.1. = derasional landforms; 2.1.1.1. = gullies; 2.1.1.2. = derasional valleys; 2.1.1.2.1. = derasional valleys of sliding origin; 2.1.1.2.2. = derasional valleys as remodelled gullies; 2.1.2. = Accumulational landforms; 2.1.2.1. = proluvial fans; 2.1.2.2. = colluvial fans; 2.2. Karst landforms; 2.2.1. = bare karst; 2.3. = Suffosional landforms; 2.3.1. = loess bluffs; 2.3.2. = loess wells; 2.3.3. = gaps; 2.3.4. = loess pyramids; 2.3.5. = anthropogeneous loess gullies; 2.3.6. = loess plateau; 2.4. = Coastal landforms; 2.4.1. = flat shore built of limestone; 2.4.2. = flat shore built of mud; 2.4.3. = headland, spur; 2.5. = Man-made landforms; 2.5.1. = pier; 2.5.2. = human settlement; 2.5.3. = slope steps of farming origin; 3.1. = Position of Susak 1997 profile; 3.2 = Traces of Paleolithic fireplace

Interpretation of loess mineralogy

The origin of the Susak loess is evidenced by the proportions of the clay minerals illite and vermiculite. Where illite predominates, it refers to the southern foreland of the Alps as source area, while where vermiculite is more abundant, in that period the dust derived from the Appennine foreland. The thermoanalytical curves for young and old loess are shown in Figs 3 and 4. As a consequence of multiple redeposition from several directions, the carbonate contents of Susak loess are substantially lower (10-14 %) than those of typical loess in Central Europe (30 %). On the other hand, grain size is much finer, close to sandy loess. It is striking that the sand contents of loess-like deposits is two- or threefold on the average compared to deposits in the Carpathian Basin.

Landform evolution

Geomorphological investigations underlined the importance of neotectonic uplift in the evolution of the island's topography and horizontal dislocations also added to the diversity of landforms on the island. The results of field work are summarised on the geomorphological map of the island (Fig. 6). The widespread occurrence of piping and gullying can be explained by the circulation of water in loess heavily influenced by the character of underlying rocks (limestone, sand or clay), their porosity and a combination of erosional processes (gully development), first of all, marine abrasion maintaining relatively high relief. The abundance of such microforms, occasionally due to human interference, promotes the development of microclimatic conditions and the ensuing diversity of

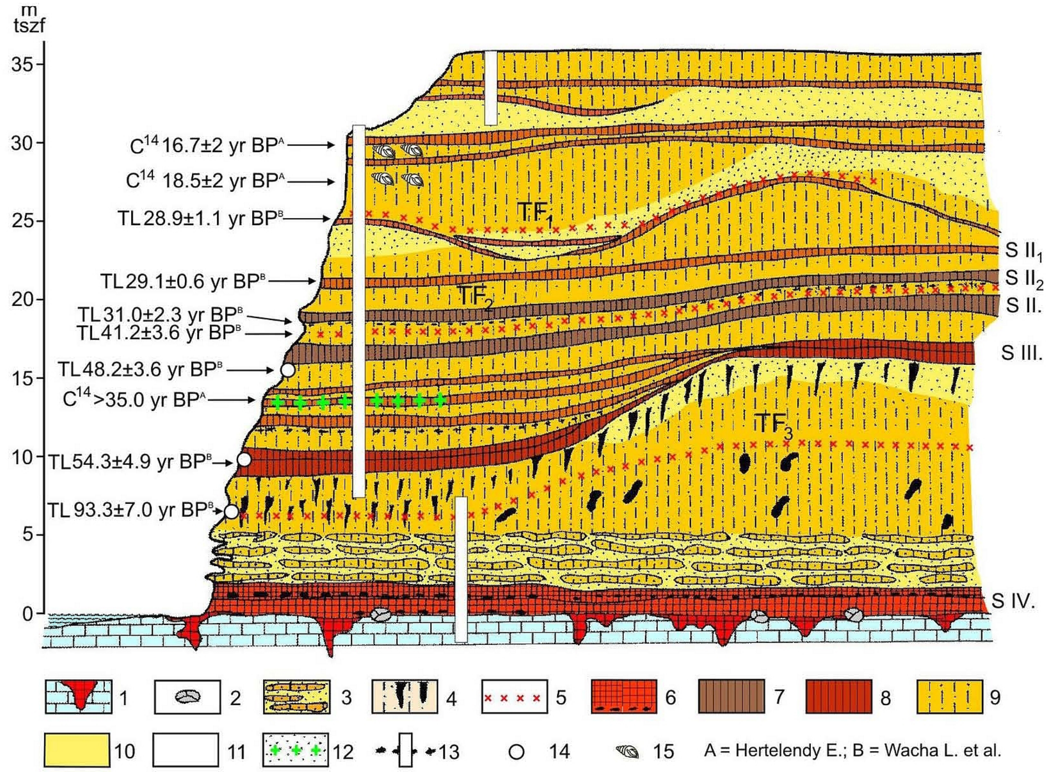

Fig. 7. Geomorphological cross-section of Susak (Compiled by F. Schweitzer) – 1 = Mesozoic (rudist) limestone, with infillings of typical red clay in the karstic depressions; 2 = ventifact; 3 = sandstone bench; 4 = loess with loess dolls; 5 = tephra horizons (TF1, TF2,TF3); 6 = reddish clays horizons of CaCO3 accumulation; 7 = chernozem paleosols; 8 = reddish brown forest soil; 9 = sandy loess; 10 = sand; 11 = charcoal horizon

habitat and biota adds to the value of the island for nature conservation.

Geomorphological observations also attest to environmental (and sometimes paleoecological) conditions. The geomorphological survey allowed a typology of loess bluffs on the island:

- Abrasionally modified high loess bluffs of more than 55º slope angle and 25-35 m (in SE) or 40-60 m height (in NW) are quite common. Topples and slumps are the most frequent processes which cause bluff retreat.
- Loess bluffs with recurring landslides are indicated by the accumulation of debris at their bases. Bluff retreat is also often maintained by marine abrasion and, as a consequence, a complex assemblage of microforms is created (Photo 7).
- Terraced loess bluffs reflect human interventions which reduce bluff stability. Thousand years of human land use (primarily vineyard cultivation) resulted in major transformation of the topography, for instance, the development of deep hollow roads (sunken lanes). After the abandonment of vineyards, a good part of hollow roads became modified into gullies or ravines by natural runoff processes.

In addition to human-induced processes, our field survey pointed out several types of natural landform evolution, which generally point to the significance of subsurface water in landform generation (exemplified by karst processes) as opposed to the action of seasonal surface runoff. At the same time, heavy downpours accelerate the evolution of

Photo 8. Corrosional and piping landforms in the east of the island, in front of the chapel (Photo by É. Kis)

Photo 9. Erosional valley in the east of the island (Photo by É. Kis)

a wide variety of loess landforms. Hollows at sites of intense infiltration broaden into loess wells, ie. deep depressions with vertical walls, or loess gorges. Loess pyramids are remnants of the original surface dissected by gullying. Loess hiatuses result from piping on exposed loess walls, where impermeable intercalation concentrate water flow into certain loess pockets which are easily eroded. All the loess landforms are high unstable and easily collapse. Ventifacts can be found embedded in red clays and their joint occurrence refers to rapid alternation of humid and arid climatic spells.

Since on Susak sandy loess varieties are predominant, typical pseudokarst features like loess dolines and loess valleys (Photo 1, Photo 9) are rare. Sand landforms occur along the coasts of Susak. The traces of ancient coastal accumulational processes are preserved in the form of paleodunes interbedded between paleosols.

4. Conclusions

The investigations support the polygenetic loess origin model for Susak Island. The dust material of loess deposits on both western and eastern coastal zones of the Adriatic Sea and its islands derives from the morainic areas and outwash plains in the foreland of the Alps and Appennines, which were unvegetated in the glacials. On the basis of sedimentological and mineralogical studies multiple redeposition and eolian, glacifluvial and fluvial transportation are assumed to carry silt to the Po Plain. From there westerly winds transported the silt material across the Adriatic basin. Since the sea level was ca 100 m below the present one and sea depth in the northern Adriatic is less than 50 m, the of the basin desiccated floor during the peaks of arid glacials. The branches of the Po River intruded far onto the basin floor. The high rate of weathering of the Susak loess also indicates long transport distances and complex history of dust particles.

The paleoenvironmental information derived from the multidisciplinary analyses of the loess-paleosol sequence of Susak is invaluable. The large amounts of sand in the deposits point to more climatic variability within the cool periods. Spells of gradual cooling are identified. The deposits typically indicating cold conditions (loess formation) are only common in the uppermost third of the sequence.

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