# Reconstruction of the Geoarchaeological Landscape of Zominthos (Central Crete) Using Geophysical Prospection, Geomorphological Investigations and GIS

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**Abstract**

In Mediterranean mountain areas, karst forms may serve as useful geoarchives for palaeoenvironmental reconstructions. Due to their function as traps for sediments from surrounding slopes, huge amounts of loose material are accumulated within these depressions, providing important information about geomorphodynamic oscillations and human-environment interactions during the Holocene. By using preliminary GIS-studies and geophysical prospection methods, in particularly earth resistivity tomography (ERT) as well as subsequent sedimentological analyses, the project focuses on the landscape evolution in the surroundings of the Minoan settlement complex of Zominthos in central Crete. The application of a multi-method top down approach offers promising prospects to future geoarchaeological research. The aim of the paper is to demonstrate the potential of this geoscientific approach for detailed archaeological purposes. Furthermore, the interconnection of techniques is of prime importance, as it helps to obtain more precise results than single methods.

**Keywords**

Geoarchaeology, GIS, remote sensing, karst, geoarchives, earth resistivity tomography, Crete

## 1. Introduction

Numerous reconstructions of ancient landscapes have been successfully conducted in the last few years and thus increasingly attracted the interest of archaeologists and geoscientists, particularly in terms of transferability to other regions and so far unstudied areas (Brückner 2007; Faust *et al.* 2002; Fuchs 2007; Vött *et al.* 2006). As presented in this paper, using a multi-component approach based on preliminary GIS and remote sensing investigations, topographic surveying, subsequent geophysical prospection and sedimentological analysis of geoarchives (colluvial fillings of karst depressions) can significantly support the investigation of palaeoenvironments and offer new possibilities for future geoarchaeological work.

The main focus of the project is on the Ida Mountains (central Crete) which are characterised by several remains of the Aegean Bronze Age (Neopalatial period, ~1650 BC) on a karstified high plateau at 1200m a.s.l. (Bonnefont 1972; Fassoulas 2000). Since the recent climatic and geoecologic conditions are very unfavourable for human purposes, the upper limit of modern settlement activities is located at about 700m a.s.l. (Sakellarakis and Panagiotopoulos 2005). Therefore, the crucial question is how and why Bronze Age people were able to live in such a remote and inhospitable region. In collaboration with the current archaeological excavations, the main research objective is to investigate the environmental and anthropogenic parameters in the surroundings of the so far unexplored plain of Zominthos (*Fig. 1*) in order to reconstruct the palaeoenvironmental conditions and processes in Mid and Late Holocene. Geoarchives like karst depressions are of special interest in this context because they serve as sediment traps. Different types of colluvial materials have been preserved here from erosion and transport into lower elevations of the island. The stratigraphic position of sediments within the dolines supports the identification of a landscape evolution chronology and associated palaeoclimatic phases.

## 2. Materials and methods

The research is based on a multi-method top-down approach with initial wide-area surveying leading to single locations for detailed field studies. Geophysical prospection (on-site and off-site) and subsequent percussion drilling finally allow geomorphological and geochronological interpretations in the context of more than 3500 years of settlement history.

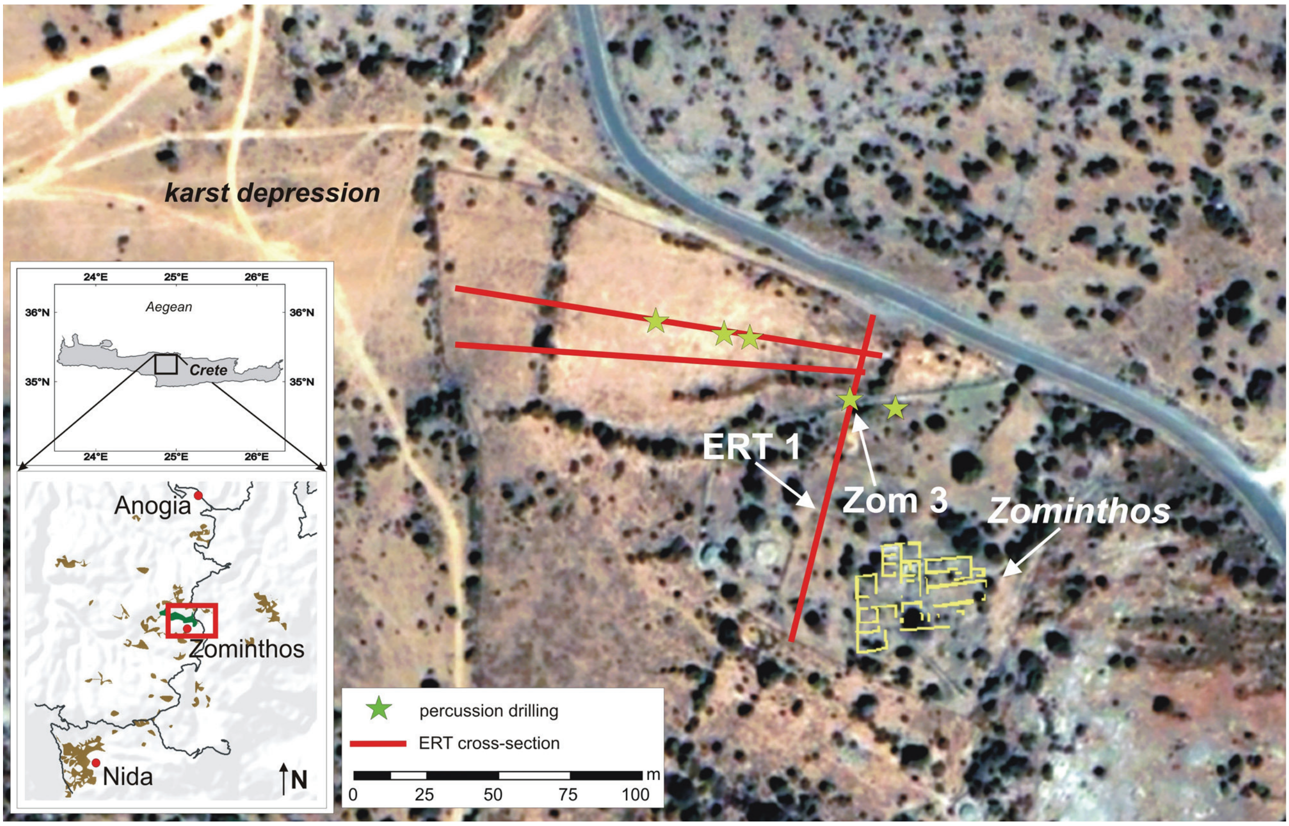


*Fig. 1. Map of the study area with location of ERT cross-sections and drilling points (Quickbird MS satellite imagery, archaeological data according to Sakellarakis and Panagiotopoulos 2005).*

### 2.1. Topographic mapping, remote sensing and GIS-studies

As topography is one of the most persistant variables over millennia, it is of major importance for geomorphological and archaeological investigations. Hence, relief data were collected by total station measurements (Leica TPS 700) during several field campaigns and finally converted into a high resolution digital elevation model (1.5m spacing). Postprocessing of data (interpolation, filtering) was carried out with ArcGIS 9.2, ERDAS Imagine 8.7 and Surfer 8 software packages. Additional environmental variables were mapped and surveyed, e.g. petrography, geomorphology, hydrology and vegetation (Siart 2007; Siart *et al.* 2007).

For area-wide analysis of the current environmental setting, remote sensing applications on the basis of Quickbird multispectral imagery (acquisition date: august 2002) were considered the most cost and time effective methods. Spatial enhancement such as pansharpening (final resolution 0.6m) and spectral image processing (ratio calculation, e.g. iron-oxide and vegetation-index) was carried out prior to the selection of training areas for 21 land cover classes. A supervised classification was prepared by using all stacked high resolution bands and the indices. The classifying algorithm itself was based on a hybrid parallelepiped maximum likelihood approach (Siart *et al.* 2008a), achieving better results than other classification techniques because of better pixel allocation control. To deal with final classification errors (redundant details, mismatch of classes) postprocessing techniques focused on statistical filtering for image smoothing. The data were converted into vector format afterwards. Since regional geomorphological maps are still unavailable and since the spatial distribution of karst depressions is of prime interest, all classified karst signatures were extracted and cartographically mapped on a scale of 1:30,000 (*Fig. 2*).

The acquisition of topographical information, e.g. contours of altitudinal zones, slope rasters and drainage system, was achieved by parallel analyses with several DEM (SRTM 90m; ASTER 15m). Furthermore, the high resolution elevation model based on field investigations and GPS surveying was applied for spatial analysis in the GIS environment.

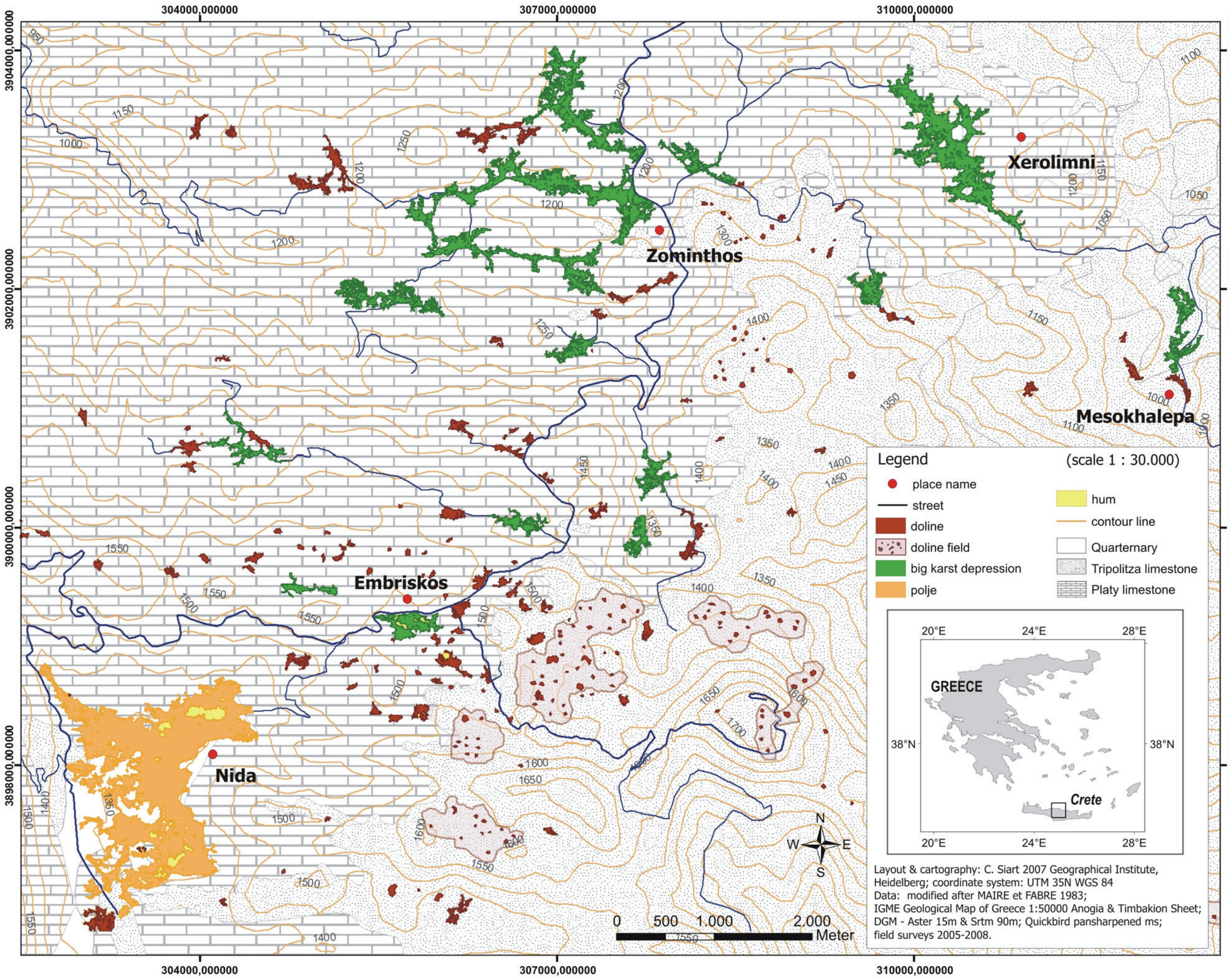


*Fig. 2. Karstmorphological map of the central Ida Mountains (scale 1:30,000).*

## 2.2. Geophysical prospection

Using modern geophysical prospection methods may contribute essential information to palaeo-environmental reconstructions and geomorphologic investigations. As such studies have been successfully elaborated in previous studies (Hecht 2001; Hecht 2003; Hecht and Fassbinder 2004), their application was transferred to sedimentary archives in a karstic environment in order to evaluate the maxium depth of colluvial fills and the stratification of sediments. In this context, the preliminary localisation of the best and most suitable geoarchives was accomplished on a large scale on the basis of the geomorphological map.

Due to its enormous size (ca. 2 ha) and its favored geoecologic setting (hydrologic benefit and springs, different rock outcrops, medium elevation a.s.l.), the depression of Zominthos was chosen as the main study area. Local resistivity tomographies (ERT) were used to analyse the differentiation of loose sediments and subsurface archaeological remains nearby the Minoan settlement complex (*Fig. 1*). A 100 electrode system was used with either Schlumberger arrays within the dolines, allowing better depth penetration than other configurations (Hecht 2007; Hecht *et al.* 2008), or dipole-dipole arrays in proximity to the archaeological site for better detection of vertical subsurface structures. Data processing was carried out with Res2DInv software, while elevation data from total station mapping were included for topographical correction of profile sections.

## 2.3. Sedimentological analyses

The ERT cross-sections allowed the determination of the most promising karst archives for selective percussion drilling on the micro-scale. All positions of the best geoarchives were selected according to the distribution of resistivity values. Subsequent percussion drilling with sample tubes (5cm in diameter) was conducted to obtain sediment cores and to accomplish chemical and mineralogical analyses. The sediment cores were drilled close to the archaeological site of Zominthos, predominantly in areas with deep accumulation of loose materials thus providing a high probability of comprehensive environmental records *(Fig. 1)*.

Several samples of organic material were extracted from the tubes and used for radiocarbon dating (AMS-$^{14}$C) to investigate the chronology of sedimentation and the age of colluvial fills within the karst depressions. Grain-size analyses, X-ray diffractometry (XRD) of clay minerals and scanning electron microscopy (SEM) of light minerals were conducted in order to identify former geomorphodynamic oscillations.

## 3. Results and discussion

All remotely sensed classification results were of good quality due to the high spectral resolution of Quickbird imagery and the preliminary selection of subclasses, which were reclassified into six major categories afterwards (parent rock, sediment & soils, forest, matorral, phrygana, grass & thorn-cushion communities). The recoding process provided more reliable outcomes, avoiding wrong class allocation of pixels in case of applying too few subcategories. When compared to areal ground truth, the overall classification accuracy reached 91.5 % with a Kappa coefficient of 0.89. Depending on the spectral classes, producer's accuracy (74 to 100 %) and user's accuracy (60 to 100 %) mostly exceeded 90 %. The final conversion results (vector format) were subdivided in to different karst forms according to size (e.g. dolines, uvalas, poljes). A significant cluster of big depressions especially emerges at medium altitudes (~1200m a.s.l., *Fig. 2*) because of favourable climatic conditions and limestone susceptible to area-wide karstification (Siart 2006).

Due to a common uncertainty about the thickness of the sediment fills and their vague suitability for palaeoclimatic research, karstic geoarchives have only rudimentarily been investigated on Crete (e.g. by Bartels 1991; Hempel 1991; Poser 1976), even though colluvial deposits can provide precious ecological data (Leopold and Völkel 2007). Our off-site ERT results actually show that the depressions are sometimes filled up more than 15m by loose materials and offer valuable information about the environmental history. Furthermore, simultaneously conducted on-site investigations demonstrate that the dimensions of the nearby Bronze Age settlement are far bigger than actually indicated by superficial findings (Siart *et al.* 2008b).

The ERT-profile Zominthos 1, measuring a total length of 120m (unit electrode spacing of 1.2m) shows a cross-section through the hill of Zominthos, which is characterised by significant subsurface structures. The different colours (*Fig. 3*) represent varying resistivity values in the underground and provide information about the composition of sediments. High values (red, violet) indicate bedrock and/or probable remains of potential walls, whereas low values (blue, green) in the shallow subsurface (R<100 Ω*m, blue colours) indicate a significant colluvial filling with fine-grained material. Values higher than 600 Ω*m (yellow, orange) show different substrate characteristics (most likely coarser grainsizes). A preliminary interpretation exposes several walls (partly tilted over?) reaching a remarkably similar height level (top edge at ca. 1175m asl). The morphological and topographical situation allows the assumption of boundary drainage channels, that might have been constructed by Bronze-Age people to catch small springs for water use and to prevent the surrounding agricultural areas (dolines) from flooding. Superficial limestone slabs are terrace remains.

Sediment core Zom 3 was drilled in a potential former drainage system (*Fig. 3*, vertical rectangle). It was utilized for subsequent mineralogical and geochemical analyses in the Laboratory for Geomorphology and Geoecology at the University of Heidelberg. As the results show, granulometric analyses are of prime importance in this context, because they indicate former sedimentation conditions. Moreover, they can be used to calibrate the ERT profiles.

The depth distribution of particle sizes shows a significant stratification, represented by a sequence of coarse detritus, clayey fine-grained materials and a colour change from reddish (hematite) to brown horizons (goethite). In addition, several big rock fragments appear in various horizons.

Since the drilling location of the sediment core was chosen on the basis of measured ERT profiles, the outstanding cluster of low resistivity values (*Fig. 3*, left, blue colours) can be correlated to the sediment stratigraphy afterwards. The results clearly show that low resistivity corresponds to fine grained loose sediments while higher values represent coarser material.

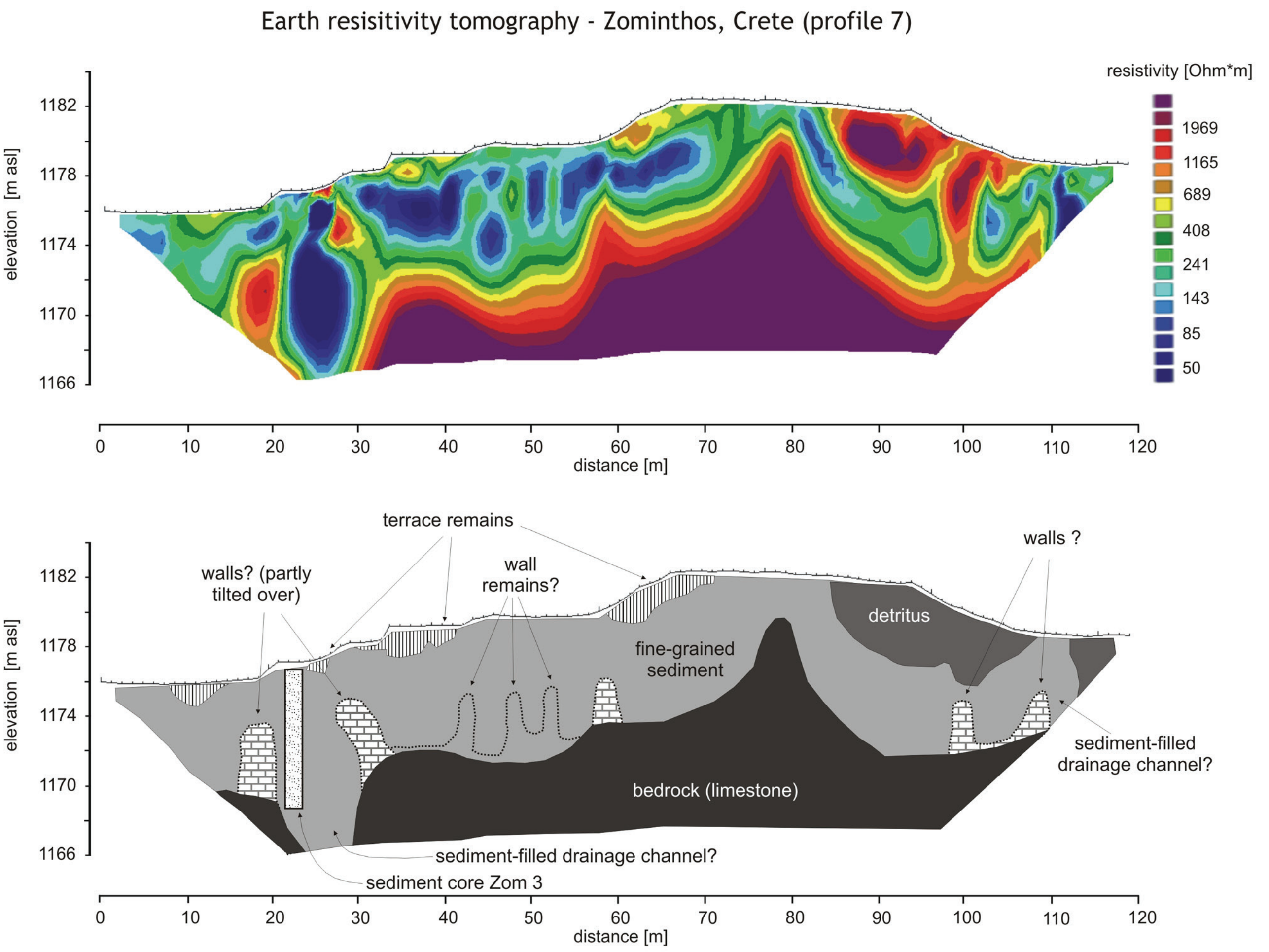


*Fig. 3. ERT profile crossing the hill of Zominthos (above) and preliminary morphological interpretation of subsurface finds (below). A dipole-dipole array with 100 electrodes and 1.2m spacing was applied.*

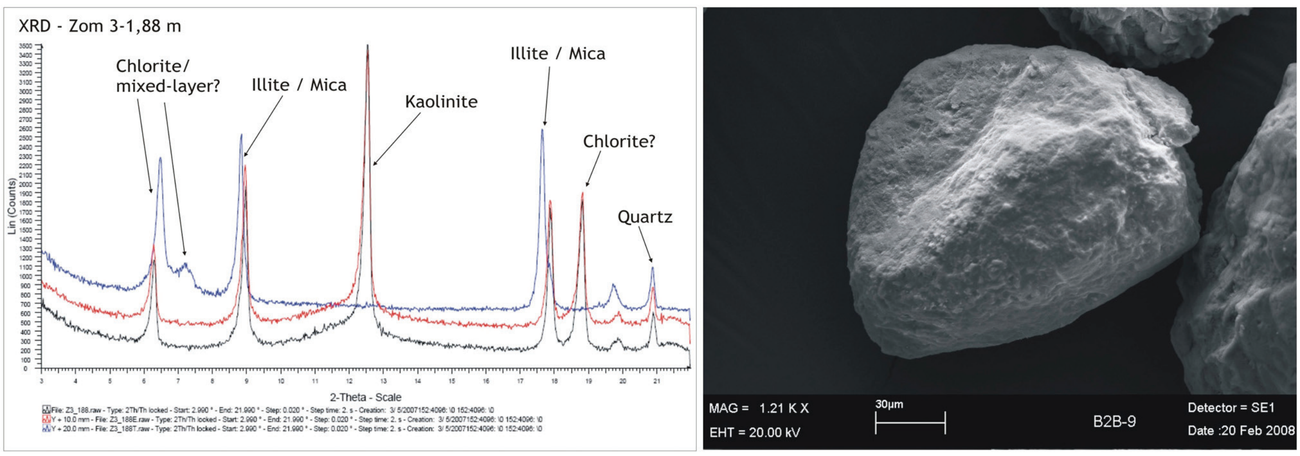


*Fig. 4. XRD diagram of Zom 3 in a depth of 1.88m (left). SE-image of aeolian transported quartz grain analysed by scanning electron microscopy (right).*

Preliminary XRD-analyses of clay mineral spectra provide information about the different provenance and weathering conditions of materials. The analysed fractions (<0.02mm) are mainly characterised by illite 10 Å minerals and chlorite or mixed-layer clays, indicating autochthonous origin and in-situ formation (*Fig. 4*, left). However, the significant 7 Å peak in most samples points out the presence of kaolinite, which usually does not inherit from parent limestones (Pye 1992; Rapp and Nihlén 1986; Nihlén and Olsson 1995). It is rather connected to long-term soil formation under tropical climates due to destruction of clays. On the other hand, some single samples that were explicitly identified as in-situ products by immediate adjacency to rock fragments in the core, are lacking in kaolinite. Therefore, one can assume a significant external contribution to local colluvium caused by aeolian dust and its deposition. This fact must be considered in combination with southern wind directions, transporting Saharan loess to Mediterranean areas. As described by Durn (Durn 1993) or Foucault and Mélières (Foucault and Mélières 2000), similar sediment characteristics are very common in Mediterranean soils and North African provenance can be assumed to a certain degree.

The methodological interconnection with XRD studies can be demonstrated by SEM analysis of light-minerals. As referred by Bubenzer and Hilgers (Bubenzer and Hilgers 2003), quartz grains may significantly be affected by aeolian transport (chipping, rounding of edges) and thus also allow provenance prediction. The analysed quartz grains of sediment core Zom 3 (0.063–0.2mm) often show such well rounded structures, serving as an evidence for windblown material and supporting the results of the X-ray diffractometry. Superficial upturned plates result from mechanical abrasion by colliding grains (*Fig. 4*, right). Current analyses therefore focus on a comparison with studies from complementary areas of origin (Bubenzer *et al.* 2007; Bubenzer and Riemer 2007) for a better definition of provenance and for eliciting potential climatic teleconnections in the eastern Mediterranean (cf. Issar 2007).

Selected horizons of sediment core Zom 3 were used for AMS radiocarbon dating. Two corresponding ages of 3360–2882 BC cal (profile depth: 3.8m) and 4991–4770 BC cal (profile depth: 4.88m) confirm the successful applicability of geochronological methods in karstic geoarchives and demonstrate their necessity for further studies (Siart *et al.* 2008b). As for the time scale, the sediments close to Zominthos do not only span a period from the mid-Holocene (mid-Neolithic) up to the present day. Moreover, they cover the important Minoan era, which is of prime importance for the palaeoenvironmental reconstruction in a geoarchaeological context, and both the differentiation of anthropogenic and environmental impacts and the detection of their interactions.

## 4. Conclusions

Applying a set of modern geoscientific methods for archaeological purposes is of great value for the reconstruction of landscape evolution processes. Moreover, the appropriate interconnection of techniques can be the crucial factor of success for geoarchaeological investigations.

As documented by geophysical prospection results, karst depressions may serve as valuable environmental archives, especially in areas with an absence of marine, limnic or fluvial sediments. The ERT profiles also show that the archaeological site of Zominthos has a bigger extent than ever expected and that human-environment interactions in the Ida Mountains were evidentially intense throughout millennia. Varying mineral compositions within the sediments lead to the conclusion that different landscape shaping processes, which are not fully explored yet, must have occurred during the mid and late Holocene. The reconstruction of the paleao-environmental and climatic conditions in central Crete must therefore consider phases of strong dust deposition due to climatic or meteorologic oscillations on the one hand, as well as strong local impacts like petrography, vegetation, precipitation or human influences on the other hand. As for geoarchaeological research, those geoecologic transitions must be given priority because environmental changes evidentially had an enormous impact on the behaviour of ancient civilizations (De Menocal 2001; Eitel 2007), such as the Minoans.

The presented interdisciplinary approach can be seen as a successful example for joint geoscientific and archaeological investigations providing a better understanding of environmental history in the context of settlement history. Since several open questions still remain, future studies and analyses will be carried out in additional depressions to check and support the previous results and theories.

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