I - EXECUTIVE SUMMARY

This synthesis, initiated during the meeting, was consolidated thereafter by inputs received from the participants.

1. INTRODUCTION

The workshop took place from 22 to 25 October 2003 on the Greek island of Santorini, one of the best Mediterranean examples of a major geological/ catastrophic event in recent times, often regarded as the birthplace of a persistent legend of universal appeal - the myth of Atlantis.

Sixteen scientists from eight countries (see list at end of volume) attended the seminar convened at the invitation of CIESM. They were warmly welcomed by Frederic Briand and Jean Mascle who recalled the main objectives and background of the meeting and expressed their appreciation for the valuable logistic assistance provided by the two Greek participants.

Workshop's objectives and outlines

The geological record reflects complex interplays between long, medium and shorter gradual trends on the one hand (for example tectonics, subsidence, erosion, sea level variations, climatic fluctuations) and instantaneous, or catastrophic, events on the other. Determining a precise chronology, assessing the spatial impacts of such events, quite often present unrealistic challenges in the absence of unambiguous correlations with reliable time records.

This Workshop was precisely designed to address such challenges, by taking advantage of the specific geological environment and rich historical and cultural heritages of the Mediterranean / Black Sea region. Indeed few places in the world offer the possibility to correlate recent geological/environmental evolution with such a rich palette of human records. The participants therefore were largely concerned with the period broadly covering the last 20,000 years in the Mediterranean area and immediate surrounding : this period coincides with human prehistory and recorded history – a time when the expression of crustal (tectonics, isostasy), sedimentary and palaeoclimatic processes, as well as of short-term events, such as earthquakes, volcanic eruptions, tsunamis and floods, is rather well documented, thanks to continuous human settlements and to the testimony left by a large variety of cultures.

Considering the general tectonic setting, one must bear in mind that the western Mediterranean and the Black Seas are tectonically somewhat passive basins, while the eastern Mediterranean has continuously been tectonically active, even during the Quaternary, in response to global plate tectonic readjustements and particularly the subduction/convergence between the European and African plates. This difference will be reflected in the archaeological and historical records.

Unfortunately, large spatial and regional heterogeneities blur the relevant available data. As a result theories and controversies about spatial extent, magnitude, frequency and impact of such events do abound. A major aim of the seminar was to review – on the basis of the latest scientific findings and available tools – the degree and reliability with which major geological processes and trends have been recorded by man during the past millennia.

Presentations linking catastrophic events such as floods, volcanic eruptions, tsunamis, with current hypotheses concerning Noah's flood, the loss of mythical Atlantis, the collapse of the Minoan civilization, or more generally with the birth of myths/legends, were, as expected, the subject of vivid debate. Other natural events receiving attention were those short events with damaging or devastating consequences (from a human perspective) on a more regional scale, e.g. neotectonic sub-vertical movements affecting certain coasts, or inland deformations connected with earthquakes (co-seismic deformations). The participants also considered and discussed the rates and impacts of more or less continuous geological phenomena – e.g. delta progradation, progressive land subsidence or uplift, and of global sea level and climatic fluctuations – and their interrelation with the relatively brief period of human history.

In all cases the coincidence – or lack of it – between available human records and geological chronological evidence was the object of scrutiny. Man has documented past environmental history in two ways: casually or deliberately. The first type, casual records, deals with archaeological remains that can be used in order to refine the precision of relative sea-level changes and shifts in the shoreline (e.g. migration of harbour sites, progradation of deltas, submerged cities) or of catastrophes. The causes may be changes in sedimentary budget, tidal dynamics and tectonics, as well as earthquakes or volcanic activities. The second type, deliberate documents, deals with historical data, such as literary evidence, paintings, ancient photographs and instrumental records. The applicability of these indicators is not as easy as it seems at first sight, as written sources often leave room for translation and interpretation. Evaluating the precision and applicability of these indicators is an important challenge.

2. TIME - SPACE SCALES

In order to properly assess, and ultimately understand, the complex interactions between the many parameters affecting geological/environmental evolution during the last 20,000 years, one must fist carefully consider the issue of time/space scales (see Petit-Maire, this volume). Three distinct time-space scales, tentatively illustrated on the diagram of Figure 1, may be recognized :

- A short scale (days and years)

Weather variability (including anomalies such as hurricanes, storms, floods and droughts) induces short but strong *local* effects upon the environment and man. Earthquakes, volcanism, tsunamis, landslides, belong to this category of events which, although relatively local in space and short in duration, may induce severe problems to human settlements, habitats, or health.

- A middle scale (one to a few centuries)

Variations in the activities of the sun, reflected by the frequency of sunspots and auroras, and by ^{14}C production, may induce significant *regional* effects (a few tenths of degrees C in temperature) upon the Earth's climate. Until recently, these processes were mainly recorded in Europe but nowadays data from both hemispheres point to the role of solar energy variations. The early Middle-Age Optimum, when Vikings raised cattle along Greenland coasts and when wine grew in Britain, and the Little Ice Age, responsible for the 16th/17th centuries' cold spells and bad crops, are good examples of these mid-scale climatic events which have direct impacts on socio-economical and political structures. A number of historians have suggested that the European revolutions in the 18th century were partly induced by the severe life conditions due to such mid-scale cooling.

- A longer time scale (millenia)

It is well established that the Milankovich orbital changes induce major environmental *global* changes. The ocean surface temperatures, recorded in oceanic and ice cores, may vary by about 7°C between glacial and interglacial peaks. Sea level changes of several meters to tens of meters, extension or reduction of permafrost areas, islands, or tropical deserts, interconnections between
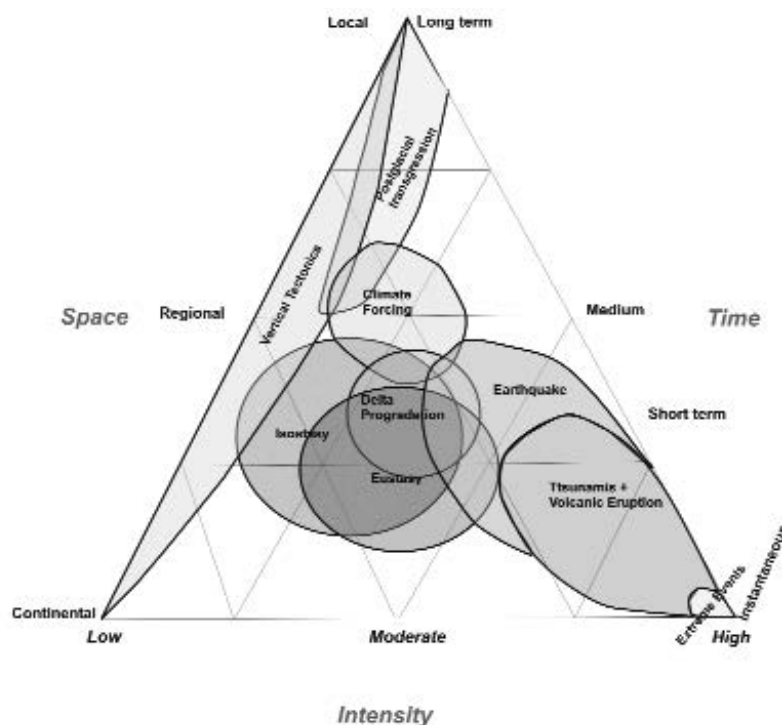
Fig. 1. Interaction of time and space scales with geological processes intensity.

emerged continental areas, delta progradation, … all relate to this time scale of events. Mankind is clearly very sensitive to such changes, especially those related to sea level (at times quite rapid although rarely catastrophic), permafrost (or ice) cover and deserts. Glacial conditions, for instance, allowed human migrations from Siberia to Northern America and, possibly, the early settlement of Australia during a Mid-Pleistocene glacial period. Around the Mediterranean Sea, the societal and political impacts of such large-scale climatic changes have been considerable, in particular during the Holocene. Throughout the Old World, the Neolithic revolution was associated with global warming and the onset of more favourable humid conditions after the precessional maximum around 11,000 BP. In contrast the arid period starting around 4,000 BP is associated with the collapse of several civilisations (Mesopotamia, Anatolia, Egypt, Indus, …) through droughts, invasions and subsequent political changes.

3. PROGRESSIVE GEOLOGICAL TRENDS

3.1. A need for a precise methodology

To analyze these classes of events precise methodologies must be used, or developed. As an example, a general sketch of the methods applied in geoarchaeological research, and of their connections, is shown in Table 1.
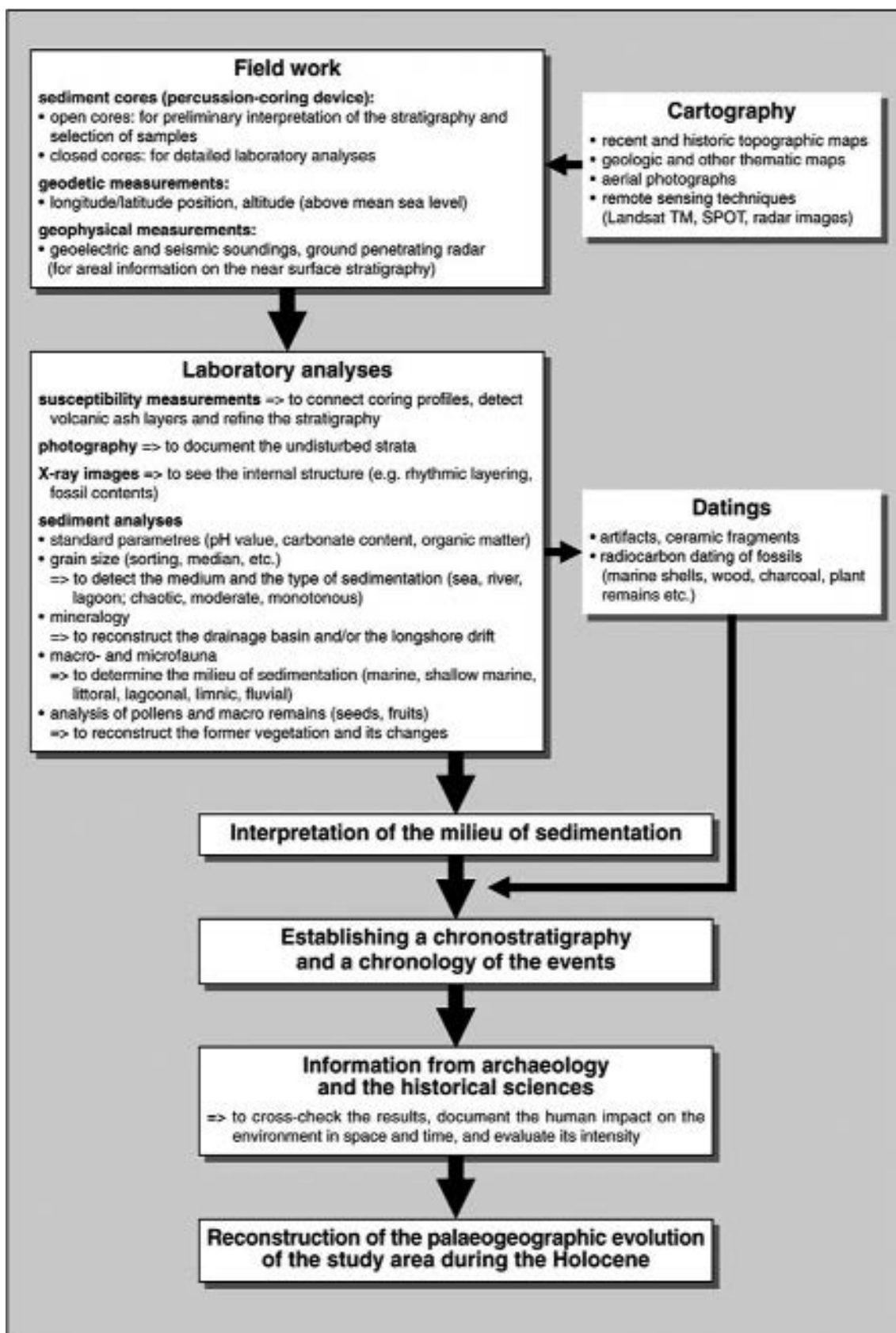
In relation to this section, the following issues received particular attention during the workshop discussions:

3.2. Dating methods

Three types of dating techniques are usually applied: radiometric, archaeological and historical. Each of them has its own applicability (material, dating range), resolution and limits.

(a) For the Holocene the usual *radiometric dating method* is the radiocarbon technique (^{14}C). It was agreed that the ^{14}C method yields the best results when applied to organic macro remains such as grape seeds or olive stones. As far as marine carbonates (e. g. marine shells) are concerned, there are still problems with the reservoir effect, all the more so since little is known about its local variations or temporal changes during the last 20, 000 years. A solution might be a cross-checking with TIMS-U and multicollector ICPMS-U series dating.

Table 1. Methods of geoarchaeology and palaeogeography (adapted from Brückner).

Field work

sediment cores (percussion-coring device):
• open cores: for preliminary interpretation of the stratigraphy and selection of samples
• closed cores: for detailed laboratory analyses

geodetic measurements:
• longitude/latitude position, altitude (above mean sea level)

geophysical measurements:
• geoelectric and seismic soundings, ground penetrating radar (for areal information on the near surface stratigraphy)

Cartography

• recent and historic topographic maps
• geologic and other thematic maps
• aerial photographs
• remote sensing techniques (Landsat TM, SPOT, radar images)

Laboratory analyses

susceptibility measurements => to connect coring profiles, detect volcanic ash layers and refine the stratigraphy

photography => to document the undisturbed strata

X-ray images => to see the internal structure (e.g. rhythmic layering, fossil contents)

sediment analyses
• standard parametres (pH value, carbonate content, organic matter)
• grain size (sorting, median, etc.)
  => to detect the medium and the type of sedimentation (sea, river, lagoon; chaotic, moderate, monotonous)
• mineralogy
  => to reconstruct the drainage basin and/or the longshore drift
• macro- and microfauna
  => to determine the milieu of sedimentation (marine, shallow marine, littoral, lagoonal, limnic, fluvial)
• analysis of pollens and macro remains (seeds, fruits)
  => to reconstruct the former vegetation and its changes

Datings

• artifacts, ceramic fragments
• radiocarbon dating of fossils (marine shells, wood, charcoal, plant remains etc.)

Interpretation of the milieu of sedimentation

Establishing a chronostratigraphy and a chronology of the events

Information from archaeology and the historical sciences

=> to cross-check the results, document the human impact on the environment in space and time, and evaluate its intensity

Reconstruction of the palaeogeographic evolution of the study area during the Holocene

(b) In an *archaeological context*, in situ ceramics and other artifacts can provide relative dating as well, but with a degree of precision open to debate.

(c) *Historical sources and literary evidence* are numerous; they are however heterogeneously available for time and space in the Mediterranean and Black Sea regions. In addition, they face several problems: proper translation, interpretation (e.g. of timing and site location), epigraphy and exegesis, as well as subjective interpretation of sources. Written sources have the additional problem of dating (type of calendar used). Iconographic representations are not always objective, except in the few cases where a "camera obscura" close to photographic precision was used (see Camuffo, this volume). Therefore, a multidisciplinary approach is needed to assess the reliability and interpretation of the data.

3.3. Sea level indicators

In general, several types of sea level indicators, each of different quality and accuracy, can be considered : *sedimentological, geomorphological, biological, pre-historical, archaeological, historical and instrumental*.

Proxy sea level indicators provide information about pre-instrumental sea level positions. Biological indicators have proven to be best in microtidal environments like the Mediterranean Sea (Laborel and Laborel-Deguen, 1994). For the northwestern Mediterranean Sea mid-littoral for example *Lithophyllum* rims are well adapted. In warmer waters, along the eastern and the southern shores *Dendropoma* bioconstructions are the most precise indicators. In protected environments, such as ancient harbours, the upper limit of marine organisms (e.g. *Balanus* incrustations and *Lithophaga* perforations of archaeological structures) may provide precise biological sea levels down to a few centimetres (for details see Morhange, this volume).

Coastal archaeological structures (fish pond, quay, jetties, pits) can also be useful sea level indicators. The precision of sea level reconstructions based on shipsheds and slipways is not as accurate because the practical relation between sea level and naval architecture/structure is not well known. Such indicators should therefore be combined with others. In general, it is always better to cross-check the produced data with another method in order to assess whether palaeo-sea level is precisely indicated. Depending on the method and the available data, the temporal precision can be decennial or even better.

Bio-erosion notches and mid-littoral abrasion platforms are very sensitive indicators (see Fouache, this volume); however, their link to sea level is still being debated as the retreat point of a notch corresponds to a locally dynamic high energy environment. As erosional features they cannot be dated directly. From a sedimentological point of view, littoral facies are typical, if not very precise, sea level indicators. From a geomorphological perspective the same is true for all kinds of coastal features such as sand spits and beach ridges.

Based on the quality and number of sea level indicators available, *local palaeo-sea level curves* can be reconstructed for a given region (see Sivan, this volume). There is however no single Holocene sea level curve for the whole Mediterranean or Black Sea since too many local and regional factors are involved and interfering (Moerner, 1996). Local curves may however – with restrictions, and presented as 'envelope curves' – be transfered to regionally valid scales.

As a very general trend, and as supported by evidence from prehistoric submerged caves from the northwestern Mediterranean Sea (Collina-Girard, this volume), **it can be stated that sea level rose from -135 m around 19,000 BP (last glacial maximum) to around 1 meter below its present position around 3,000 BP.**

Sedimentary input increased when sea level rise decelerated at about this time (Stanley and Warne, 1994). Then the impact of Neolithic deforestation, as well as longshore sediment transport, led to massive and rapid changes of coastal landscapes. The implications for mankind are obvious, for example in the shifting of coastal settlements, or with harbour migration (see Brückner, Vött, this volume).

Palaeo-environmental proxies

While *bio-sedimentological evidence* of palaeo-sea level is easily detectable, it does not provide very accurate estimates at those levels. It is a useful tool for palaeo-climatological and palaeo-

geographical reconstructions which aim to outline the location of former shorelines. *Palynological* studies, for example, can help to determine marine transgressive facies with marshland development parallel to the shoreline (Beckenbauer, 1962; Galili and Weinstein-Evron, 1985).

When reconstructing delta progradation, *microfaunal* studies (e.g. ostracod or foram analyses) help establishing the direction and rhythm of sedimentation as well as the different environments of deposition (marine, lagoonal, littoral, lacustrine, fluvial). *Archaeo-zoological* remains (e.g. animal bones) may also provide important data for deciphering coastal evolution, especially if they can be dated.

As detailed by H. Brückner in this volume, extensive *archaeological survey* can be fruitful in revealing interactions between landscape evolution and human settlements. Since archaeological sites are often buried under thick layers of deposits in coastal sedimentary basins, field surveys must be refined by *geophysical methods and coring*.

4. SHORT-TERM / CATASTROPHIC EVENTS

4.1. Time-space scaling

Human records of short-term/ catastrophic geological processes and phenomena in historic and prehistoric times have to be considered as functions of event intensities and of impacts (and damages) caused on ancient human settlements and lives. Here also the time-space interaction is a major problem to take into consideration. A sketch of time-space relations between catastrophic events and their relative intensities is shown in Figure 2.
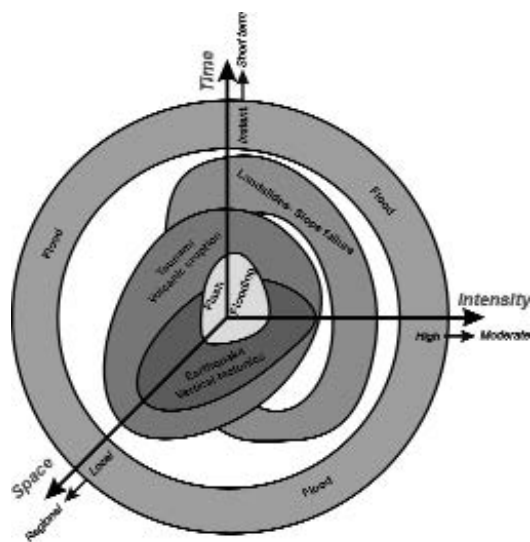
Fig. 2. Interaction of time and space scale with intensity of catastrophic geo-processes.

Usually damage increases with the intensity of an event (earthquake, tsunami, etc …) but the physical damage (e.g., the degree of city destruction) does not equate with the extent of the permanent change printed on the landscape. Indeed slow tectonic processes working on larger time-scales (e.g., surface uplift and/or subsidence) can be more effective as landscape changers than catastrophic events. These processes can induce dramatic geomorphological (and environmental) consequences when they interfere with fluvial systems and alter the fresh water budgets of large areas such as wetlands. Sometimes episodic uplift-subsidence (of seismic origin), not necessarily strong, can act as a trigger, with vertical tectonics gradually moving a fluvial system to conditions close to non-equilibrium and/or disequilibrium. Cases illustrated by P. G. Silva in this volume deal with the fluvial capture and desiccation, between 4,000 and 2,500 yr BP, of ancient Holocene wetlands presumably providing fresh water for Late Neolithic/Early Copper Age populations in the Iberian Peninsula. Such changes coincided with the post-flandrian sea level fall on the Spanish littoral and with a major climatic crisis (aridity) recorded throughout the Mediterranean region (see Petit-Maire, this volume).

Another attempt to illustrate the scale dimension of short-term natural events and their interactions with Mankind over the last 20,000 years is shown below in Table 2.

Typical time scale	Space scale	Climate	Events	Geomorphologic changes	Impact and effect on mankind
months < long < years	regional	astronomical global changes	flood	marine transgressions collapse of periglacial lakes	shifting of coastal settlements; landward migration
days < mid months<	regional to local	???????	volcanic eruption	caldera creation; filling up of lowlands with volcanic deposits	migration; socio-economic and political changes; air pollution; global warming?
hours < short < days	local to regional	extreme meteorological events, high precipitation, volcanic effects; meteorites	earthquakes landslide, tsunami, flash floods,	coastal erosion; slope slope retreat; abrupt silting up of lowlands and valleys;coseismic uplift or collapse	silting up of human installations, i.e., harbour sites.

During the workshop various short-term/ catastrophic events (in other words the catastrophes resulting from and producing geological processes) were discussed. We now review the main examples and concepts covered.

4.2. Earthquakes

Ancient accounts (from Herodotus, Pausanias, Strabo, and others) provide valuable descriptions of the impact of major earthquakes and earthquake-related phenomena on human settlements in historical times. Those scripts, no matter how precise, are only of descriptive value and clearly depend on the author's perception, or on the accuracy of the information provided to him. Their use is consequently of informative value only, as descriptions and data should be checked carefully with modern methods. Thus our knowledge of catastrophic earthquakes and of their effects on ancient cities has greatly benefited in recent years from archaeological findings (see Altunel ; Silva, this volume), although much care is required when interpreting archaeological records which may indicate vertical tectonic movements.

Quaternary seismic events can be archived within the geological record (i.e. by seismites), but abrupt landscape changes, triggered by tectonic activity during the last 20,000 years, can also be preserved in the geomorphological record. For more recent time periods (i.e. last 8,000-9,000 years) large earthquakes commonly interfered with human activity and are thus incorporated into archaeological and/or historical records. Therefore, to understand the impact of tectonic events on the environmental history of ancient populated areas, the geo-archives (geology/ geomorphology and human record – i.e., archaeology and history) should be considered together. This will help assessing the real contribution of tectonic events to environmental change.

Most of our knowledge about "long term" seismic behaviours of formerly populated regions proceeds from "historical sources" (seismic catalogues; e.g., Papazachos & Papazachos, 1989, Guidoboni *et al.*, 1994; Ambraseys and White, 1997). Only recently, during the last decade, has archaeological evidence of reported (or unreported) historical events been taken into account. In most cases evidence of major events is weak in the geo-archives, although these events can leave strong signals in the human records of localised areas. Only "extreme events" affecting larger areas can generate clear signals in the geo-archives and be perceived by ancient populations as global catastrophes, eventually incorporated into history as "Myths" (see section 5 below).

Modern geological, geo-morphological and palaeo-seismological methods are now being used to investigate the parameters of ancient seismic events and to reconstruct seismic scenarios and associated phenomena. Reconstructions of past seismic climax, with data gained from recent approach and methods, increasingly provide valuable guides to estimate the seismic potential of faults, assess seismic recurrence risk, or earthquake planning and protection. For example the destruction and subsequent submergence of ancient Helike (southern shore of the Gulf of Corinth) as a result of a strong earthquake in 373 BC, followed by coastal collapse and tsunami invasion, provide an excellent case study. They may contribute significantly to the evaluation of seismic risk in an area where similar phenomena, but of lower magnitude, are reported to have taken place repeatedly since Antiquity (see Sakellariou, this volume).

4.3. Volcanic eruptions

In contrast with earthquakes, volcanic events leave very strong signals in both geological and human records, even in their lowest energetic manifestations. Ongoing geodynamic processes at convergent plate tectonic margins are responsible for the active volcanism in the Aegean and Southern Tyrrhrenian Seas. Volcanic eruptions have repeatedly taken place during recorded history and have been responsible for some local but enormous catastrophic events.

The Minoan eruption of Santorini in the 2nd millenium BC was probably the greatest volcanic eruption to have taken place on Earth during the Holocene (see Nomikou, this volume). Closer to us in time, Pompeii is the best known example of a historic city, suddenly erased after the eruption of Vesuvius in early Christian times. Both events are extensively recorded in archaeological, geological, sedimentological and geomorphological records.

Large scale excavations have brought to light both ancient Pompeii and parts of the Minoan city of Akrotiri on Santorini Island. The archaeological data provided significant information on the various processes which took place prior to, and during, the eruptions. Geological field mapping and laboratory analyses completed the archaeological records, allowing detailed interpretations of volcanic processes (see Nomikou, this volume). Nevertheless, direct geo-chronology of volcanic material remains a challenging task and the radiometric ages obtained must be treated cautiously.

Volcanic activity and processes associated with the mobilization of magma are also responsible for vertical movements in areas adjacent to volcanic centers. Pozzuoli, in the Phlaegrean Field near Napoli provides a good example of alternating rapid uplift and collapse (see Morhange, this volume) with an important geomorphological and human impact.

4.4. Tsunamis

Records provide information on a large number of tsunamis (which can be triggered by earthquakes, volcanic eruptions and slope destabilizations) throughout historic and more recent time. Independently of the triggering mechanisms, the effects of tsunamis on the coasts and the damage to human settlements may be very significant. Tsunami deposits may, or may not, be preserved on the drowned land and, if present, may well be misinterpreted. Trenching, as a method to investigate possible tsunami deposits, allows fairly detailed reconstruction of the affected area if such deposits are preserved. Detailed palaeo-environmental studies are required to distinguish the violent and abrupt landward deposition of loose and mixed material coming from the seafloor/ or coastal zone from high-energy fluvial deposits.

Historical records and archaeological data are valuable for the dating of past tsunami events. Direct geo-chronological methods (^{14}C, U-Th, etc.) may contribute. Available information on past tsunamis and their consequences during historic time can be considered as valuable additional data towards the assessment of tsunami hazard of coastal Mediterranean areas. It is interesting to note that certain similarities can be found across time and regions between tsunami-linked coastal collapse events. For example, coastal failure and subsequent mass sliding occurred in 1979 at the airport of Nice, causing serious damage and human casualties. This catastrophic event seems to have developed in similar ways to those which led to the submergence of ancient Helike in 373 BC.

As for other short-term "energetic" geological processes, human damage caused by tsunamis may be far greater than the signal left in the geo-archives by the triggering earthquake. Thus the 1755 Lisbon earthquake (Ms 8.5 – 9) led to extensive tsunami damage along the Atlantic Iberian coast, but left only a weak geological record: modest washover fans breaking the more recent spit-bar systems (see Silva, this volume).

4.5. Flood(s)

The famous Noah's flood was the subject of much debate during the meeting. Although few participants doubt that it happened, there remains much controversy about the way it actually took place (see Lericolais, this volume).

Floods are common elements in the testimonies/ mythologies of all Eastern Mediterranean and Near Eastern civilizations (see Wyatt, this volume). To some extent it appears therefore plausible to infer that such a spatially extensive myth may be related to the Holocene global sea level rise, with particular morphological characteristics possibly controlling the timing as well as the magnitude of the flood in the various regions. But it is also possible that the flood myth may not reflect a single flood event. Chronologically and spatially successive flooding of various regions may well have led to the creation of similar myths in the testimonies of the different civilizations.

For example, as detailed by G. Lericolais in this volume, although the Global ocean sea level has risen since the end of the Last Glacial Maximum (i.e. 18,000 years ago), significant fluctuations of Black Sea water-level occurred before and since its final drowning. These Black Sea regressions and transgressions appear to be modulated by climate and directly linked to the fresh water input from the Northern ice cap during its melting. It appears that the Black Sea, when not connected to the Mediterranean Sea, behaved as a giant enclosed basin akin to the Caspian Sea, i.e., as a major receptacle for the earliest melt waters, highly sensitive to regional climate fluctuations (see Kvasov, 1975; Svitoch *et al.,* 2000). Thus, as the ice cap reached as far south as Poland at its moment of maximum extent 20,000 years ago, major rivers flowed southwards. The first important melting of the northern ice cap (Melt Water Pulse 1A; ca 14,000 years BP) provided important masses of water to the receiving enclosed basin that was the Black Sea at that time. In consequence the level of the Black Sea rose from about -120 m to an average water level of -40 m around 12,000 years BP. The arid period encountered through the Younger Dryas event and the cessation of melting water caused a drop in Black Sea water level estimated to -100 m (geophysical results obtained during Ifremer cruises), although the global ocean was "standing still" during this time. Such large-scale Upper-Pleistocene/Holocene fluctuations are evidenced in the sedimentological record and the palaeo-morphology of the Black Sea shelf. Could they have contributed, during the last rapid transgression, to the origin of a flood myth ?

Recent data from the Aegean/Ionian Sea region support the idea of successive, regionally and locally distributed flood events. Present-day semi-enclosed basins and gulfs, like the Gulf of Corinth or Saronikos Gulf for example, are only separated from the open sea by very shallow straits. For some of them it has already been shown, on the basis of stratigraphic sequences, palaeo-environmental and geochemical analyses, that they were isolated from the rest of the Mediterranean during the last glacial maximum. Thus, the timing of their drowning by the Mediterranean water is directly related to the depth of the straits (see Sakellariou, this volume).

5. LEGENDS AND MYTHS

The reliability of ancient sources (literary, archaeological, artistic, ...), as well as their accuracy was thoroughly discussed and debated, through examples such as the myth of the lost Atlantis. Much has been written about Atlantis, a great deal of it aiming to demonstrate the reality of the myth and attempting to locate the lost city. But to what extent does the myth of Atlantis reflect reality ? Or is its real value to inspire us to keep searching for alternative explanations and hypotheses and in this way to produce new knowledge? Noah's flood (see above) is another good example of a strongly debated myth or legend

The reliability of information gained from ancient sources is, in general, to be related to the ages of the sources and their origins (archaeological data, historical records, memory/ mythology) : ancient sources tend to be generally less and less accurate / reliable as they originate from older times. Thus written reports on events from the Middle Age or Byzantine time are generally more accurate than those originating from Roman or Classical times, themselves more accurate than those from earlier times. Nevertheless excellent descriptions of ancient catastrophic events do exist, either constituting exceptions to the rule, or owing their accuracy to the high magnitude of the impact.

Retracing further back into the past, the accuracy of witnesses/ descriptions diminishes to very low levels, for example, to the level of accuracy of indirect information, as decoded from the mythologies of various civilizations. But even at this level, the differentiation of myths from reality requires nuances and categorization. For example, the *Iliad* written by Homer in the 2nd millenium BC was long considered entirely apocryphal. Yet it was its centerpiece, the "legendary"

Trojan War, which led Henrich Schliemann to his many excavations and to the stunning discovery, in 1871, of the ancient city of Troy near the mouth of the Dardanelles. More scientifically elusive – at least for the time being – Flood myths are documented in the mythology of several civilizations (as Noah's Flood, Gilgamesh, Deukalion's Flood, …): they therefore deserve to be treated as having higher pragmatic value than the myth of Atlantis, for which we dispose of only one remote, indirect account, that of Plato (see Collina-Girard, this volume).

Finally, the majority of mythologists (Thomas Bullfinch, Karl Jung …) consider myths to be evidence of collective memories, of old half-forgotten events, to which religious or ideological elements have usually been added. Their origins are predominantly external. This external view of myths makes the gods' roles appear as rationalizations of experience, somewhat comparable to scientific hypotheses. If this view is accepted, then the origins of myths can be traced tentatively to the same psychological need for explanations. A difference between the two categories of explanation is that while myths tend to be pulled towards ideological poles, scientific ideas as they mature gravitate in the opposite direction, towards the epistemic. Perhaps it was the development of science and epistemology which brought an end in classical times to the great age of mythogenesis (see Wyatt, this volume).

Climatic crises and man in the Mediterranean basin : the last 20,000 years

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The climate of an area is a statistical notion defined by the average values of the meteorological parameters (precipitation, cloudliness, temperature, wind) over 30 years. We may speak of climatic change when those recorded values significantly change. We must therefore not take one or a few meteorological anomalies for climatic change.

Our socio-economic structures are, for a large part, based upon the current climate of the Earth (a 15° C average surficial temperature) and its main geographical relationships : global sea level and location of ecozones. The coastlines define the continental habitable surface and the terrestrial communication routes, while the ecozones command freshwater and vegetation availability, food production through agricultural and breeding possibilities, therefore economic systems, habitats locations and types, life styles and social organisation. Geopolitical patterns proceed from the sum of all the latter parameters.

The study of the Past, through the real archives of geological records, providing information on paleogeography, paleobiology and prehistory, has made evident that stability, not change, is the climatic rule.

On a short scale of one to a few years, volcanic activity may cool certain areas (generally latitudinal, in relation to the Earth rotation) due to the important mass of ashes thrown into the atmosphere which partly reduce the arrival of solar radiation. In the past, the major eruptions of the Tambora and Krakatoa volcanoes produced ash clouds which cooled the nearby latitudes for two to three years. The dust from large meteoritic impacts may produce similar effects; during the recent "cold war", the fear of "nuclear winters" was often evoked in a similar context.

The middle scale variations of solar activity (recorded by sunspots and auroras), induce moderate climatic changes during one to several centuries. Thus a warm period from the 10th to the 12th centuries allowed the Vikings to colonise the coasts of Greenland, vine to grow in England, and cereals to be cultivated in Ireland. In contrast, in the 17th and the 18th centuries, the "Little Ice Age" was named after cold spells which affected crops and brought about famines and… revolutions.

At the geological millenial scale, in contrast, an alternation of cold and warmer phases is commanded by pseudo-periodic astronomical changes in the Earth's orbit : the deformation of the ellipse around the Sun, the changes in the inclination of the axis relative to the orbit and the spin-like oscillations around the axis. The combination of these processes modifies the energy received from the Sun, according to its distance to the Earth and to the seasonal positions of the

globe. Paleogeographical modifications of our planet, linked with those variations, are recorded in sea floor and lake sediments as well as in the thick ice covers in the Antarctica (Fig. 1) and Greenland.
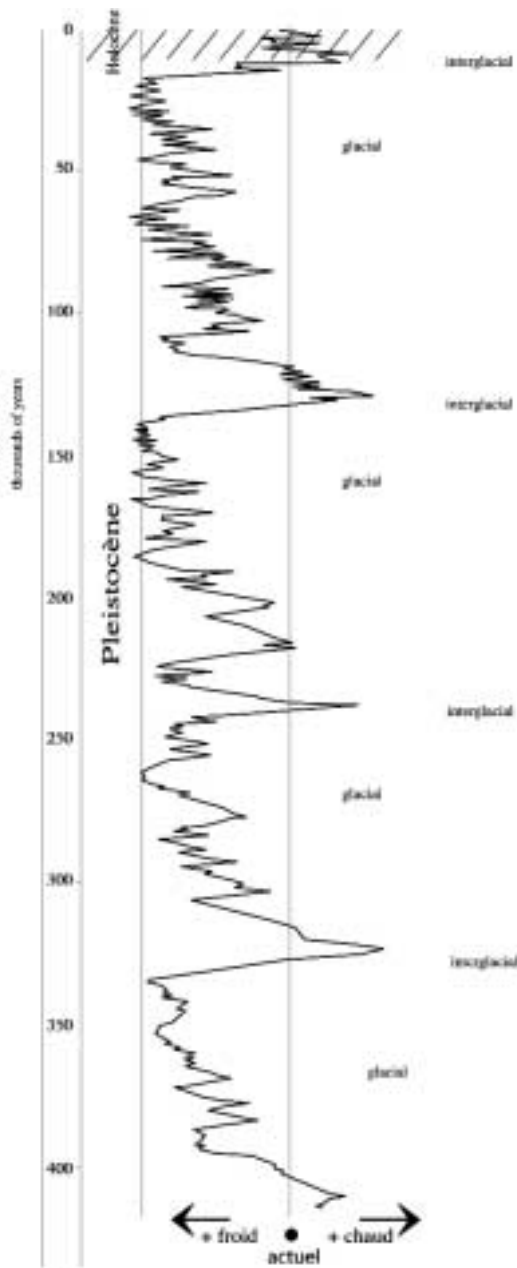
Some key periods appear in the record of the last 20,000 years before present (BP) : the last cold and warm extremes, respectively about 20,000-16,000 and 9,500-7,000 years ago, and, already historical, the crisis 4,500-3,500 radiocarbon years ago. This paper shall consider the links of these major climatic changes with civilisations and human societies in the Mediterranean Basin and its periphery.

THE LAST GLACIAL MAXIMUM

From 20,000 to 16,000 BP (radiocarbon dating), global average temperatures are 4.5° C below present ones. Due to the huge inland-sis, which blocks fresh water over the high latitudes, the oceans level is ca. 125 m lower. The Mediterranean coastlines are deeply modified, the sea being parted into three isolated basins with respective average surface temperatures of 13.7° ± 2°C (Alboran Sea), 13°C (Ionian Sea) and 14°± 2°C (Levantine Basin).

From Tunis to Tripoli, a 300 km-wide coastal plain is emerged. The islands of Corsica, Sardinia, Elba, Malta are linked to the continent by land bridges. The Gulf of Lions is a continental plain linked with Cape Nao, 100 km south of Valencia in present-day Spain. Half of the Tyrrhenian Sea is dry, most of the Ionian Sea islands are part of continental Greece, while the Black Sea is widely reduced relative to now (Lericolais, this volume). Connections between the northern Mediterranean coast and North Africa are easily established, since few marine gaps persist between Sicily, the Kerkena islands and Tunisia.

The biotopes along the coasts are still favourable to life, as the permafrost line stops around the 45th parallel and Alpine glaciers are not reaching the coast. The large mammalian fauna, emigrated from the very cold

Fig. 1. Temperature at Vostok (Antarctica) relative to nowadays (adapted from Petit *et al.*, 1999)

North, has then colonised the sea margins where it is hunted by the first *Homo sapiens* populations : coming from the Middle-East, they are extremely sensitive to the paleogeographical facilities allowing migration of their small nomadic groups into formerly insulated territories, at a time when navigation hardly exists (very probably due to the lack of wood, attested by absence of arboreal pollen throughout the area). Along the coastal plains, fish, molluscs and also – as attested by rock paintings – seals, complement the diet supplied by the terrestrial mammals. Cro-Magnon groups settle in southwestern Europe where caves provide shelter and surfaces for rock art. They migrate up the Danube river but soon reach colder regions and retreat southwards. In North Africa, their "Mechta-el-Arbi, Afalou" type is established at 13,000 BP along the Maghreb coast, reached from the Middle-East during the preceeding millenia. We shall see that, improv-

ing the opportunity of another – favourable – crisis, they will scatter, later on, very far into the western and southern Northern Africa.

In brief, the last glacial extreme, while it providing human groups with a harsh, difficult life, was a favourable period for migrations and for the geographical development of Homo sapiens along the extended coastal plains of the Mediterranean.

THE EARLY HOLOCENE CLIMATIC OPTIMUM

At the end of the Pleistocene, the progressive and irregular deglaciation of the inlandsis and mountain glaciers has brought the global sea level 35 m below the present mean sea level: an average number to consider within the wide geographical variability due to local glacio-eustatic or isostatic changes. The Mediterranean shorelines have nearly reached their modern aspect, characterised by "islandisation" of a large part of the former continental surface.The sea surface average temperatures in the Alboran, Ionian and Levantine regions are now respectively 18.3°± 0.4° C, 17.0° ± 0.9° C, and 18.8° ± 0.8° C, i.e. some 4 to 5° C higher than during the glacial extreme.

Globally, the average surface temperatures are some 2° C higher than at present. The oceanic and atmospheric circulations deeply change and, about 1,000 years after the maximal insolation peak at 11,000 BP, the biotopes quickly react to variations in the water-budget. The geography of the whole world is modified and the biosphere enters a new, very favourable phase which most of the peri-Mediterranean regions and their populations will benefit of.

Due to sea level rise, river estuaries cannot contain floodwaters from the melting of mountain glaciers and the breaking off of their moraines : lowlands are flooded. The surficial melting of impervious permafrost around the mountains results into other vast flooded areas.

In the tropical presently arid areas, seasonal wadis become perennial and lakes or swamps appear in the depressions, due to run off and groundwater rise. The very core of the Sahara is reached by both summer (monsoon) and winter (Atlantic depressions) Mediterranean precipitations. The response of the biosphere is quick, sahelian plants and animals migrate north up to the Tropic of Cancer, a Mediterranean steppe grows some 300 km south of its present limits. We dispose of some 3,000 radiocarbon ages based on paleohydrological, paleontological and archeological observations on the vast, now desertic, 9,500 km^2 between the Atlantic Ocean and the Red Sea, during the Holocene. All the curves constructed from these clearly show the occurrence and duration of the climatic Holocene favourable crisis, ending around 4,500 BP.

Satellite radar imagery shows important rivers flowing into the Nile, whose sediments could be dated at this phase. The Nile canyon, cut down into the exposed coastal plain during the glacial phase, is now flooded again by seawater. The Nile brings its fertile red loam from Ethiopia. To the East, the Taurus and Zagros mountain glaciers melt off and forests grow off their former refuges. Wild cereals proliferate and colonise the plateau : the ancestor of our corn grows up to an altitude of 900 m, together with wild barley and oats. Boars, foxes, sheep, gazelles, deer ans bos migrate into the newly habitable territories.

This 4 or 5 millenia long warm-wet crisis induced a major turn in human societies : sedentarisation and the control of nature became possible. The first villages exist at 10,000 BP in the Middle East. From 10,000 to 7,000 BP, a new civilisation emerges : the Neolithic, not only marked (as its name indicates) by more differenciated and refined lithic tools, but by agriculture and cattle breeding, invention of ceramics (since sedentarisation allows both fabrication and keeping of heavy vessels). Urbanisation soon appears and large villages (like Jericho or Çatal Huyuk) exist in the Middle East. Clanic life is abandoned in favor of an organised society, favoured by demographic expansion, particularly in the Syro-Palestinian corridor naturally protected from floods.

Domestication of several species of wild plants and animals are also linked with this explosive cultural crisis. About 10,000 years ago, the Ovis orientalis from the steppic biotopes of the northern Middle East gives rise to goat domestication. Pigs and dogs soon follow.

The Cro-Magnoid populations around the Mediterranean were widely influenced by such changes. By 9,000 BP, they follow the coast of North Africa and, at 6,000 BP, they have settled

in southern Morocco, upon the consolidated coastal dunes of Izriten. From there, they migrate to the Canary islands where they are recognized as the ancient "Guanche" population, strikingly recognisable as Cro-Magnoid. Still further, they migrated across the then steppic Sahara and are found 7,000 years ago, only 300 km north of the Niger bend, around the freshwater lakelets rich in large mammalian and reptilian fauna (at the end of the humid phase, they will again migrate southwards towards the Niger river).

These major climatic changes affected the human populations of Egypt, Mesopotamia, Syria and Palestine, in another, too rarely studied way : since the humid tropical biotopes shifted north, new plagues must have hit hard upon the unprotected communities : bacteria, and over all, parasitoses like malaria, bilharziosis and worms. Animal domestication certainly favoured new water-borne and insect-borne diseases, the number of which, shared by man and animals is high : 26 with poultry, 32 with rat or mice, 35 with horse, 42 with pig, 46 with sheep and goat, 50 with cattle, 65 with dog. It is certain that living closely with them in poor hygiene conditions multiplied new infections among the Neolithic populations of the warmest, wettest areas in the Mediterranean basin. The expansion of irrigation systems was certainly a strong diffusion factor of water-molluscs hosted schisostomiasis. However, along the Mediterranean shores, no massive irrigation was necessary to the cultivation of olive trees and no strong sign of diseases was recorded during the humid phase.

One cannot skip, in this review, the worldwide major myths (see also Wyatt, this volume), which appear related to the onset of this climatic optimum. Fear of invasion by both fresh (floods) and salt (sea level rise) waters expanded throughout the world around 9,000 years ago and lasted for at least two millenia.

The mythical Deluge therefore is the memory of exceptional events – the Early Holocene climatic crisis – which considerably impressed all the ancient human societies throughout the world. In China, the flooding of the vast plain some 500 km east to west along the Yangtse river has left memories of times "when the waters flooded the country, serpents and dragons lived there and men did not know where to stay». In India, "purification by water" is associated with strong winds from the South, i.e. exceptional monsoons. In the Pacific, Maori myths record that angry deities swallowed the atolls. In Iran, the Parsis Zoroastrian books record a time when "the poison of the world was dissolved into water, which caused the sea to become salty" and stopped an early Neolithic outburst by a period of high precipitation, rainfall and snowfall. In Mesopotamia, Gilgamesh epic, written about 5,000 years ago, describes the Babylonian myth of "diluvium : flooded lands, no sunshine, wind from the South and " swamp reaching above the house roofs", events due to the increased activity of the monsoon and of the Euphrates and Tigris flows fed by glaciers melting in the northern mountains. Geology has recorded in stratigraphical position, at Kish and at Ur, an alternation of clay layers with freshwater Molluscs and of arid formations : the first flood period is dated 9,000 BP. According to Platon's count of generations duration, the Atlantis submersion also happened at about 9,000 BP (see Collina-Girard, this volume).

Another myth in judeo-christian cultures is directly related with one of the humid holocene oscillations : the so-called "Egypt plagues" which hit the populations of the Nile valley and Delta and were interpreted as God's signs for obliging the Pharaoh to "let his people go".

• The increased run off from the Ethiopian highlands brought great quantities of their typical red loam into the Nile waters, an unusual phenomenon in a formerly arid region : hence the "bloody waters" myth.

• Snakes, toads, frogs and flies largely increased in number in the new wet biotope. It is well known that snakes and amphibians proliferate in warm humid lowlands and river swampy banks : both come out in wet weather. Even nowadays, tropical populations are aware of serpents entering dwelling places during precipitation spells.

• Mosquitoes, of course, are part of the biological changes brought about by change from arid to humid climate. "The whole soil dust was changed into mosquitoes throughout the whole Egypt and they came upon men and animals".

• Locusts flights happen in North Africa when a particularly humid year occurs and brings abundant rainfall over the Sudan region (in 1988, driving in southern Algeria, the author crushed hun-

dreds of locusts forming a thick carpet on the road. One month later , the same locusts flew from the Moroccan Sahara into the eastern Canary islands).

• Epidemics and epizooties often occur, especially in primitive unprotected societies, wherever warm and humid conditions favour bacteria development. The northern shift of ecozones due to the Holocene climatic optimum had very probably brought to Egypt new diseases and parasitosis from its southern margins. Normally, the newborn and the aged people are the first victims of such endemic or epidemic plagues.

• The main disease evoked by the mythical epics is the "pustulous dust that Moses throws to the sky and which infects Egypt" : smallpox undoubtedly, most dangerous in a fast-growing population living in poor conditions.

• Hail is one of the characteristic stormy weather anomalies which most impressed populations formerly living in desert conditions. " …the Lord sent thunder and hail and the sky fire descended upon the land… It hit all those in the fields, men and animals, it hit the green vegetation and broke the trees throughout the country".

• The Santorini tsunami is often held responsable for the drowning of the Egyptians during the flight from Egypt, although this one probably took place not along the Sinai coast, but inland where paleoswamps existed, turned into dangerous sebkhas, where vehicles still nowadays can quickly sink, while men and camels have no problem crossing.

The climatic humid critical phase will brutally be interrupted by an acute aridity spell which, again, will strongly modify man's environments and way of life.

THE CRISIS AFTER 4,500 BP

At ca. 4,000 BP, the climatic curve for the whole presently arid area in Northern Africa shows as strong a descending trend towards aridity as it had shown a steep ascent towards humidity during the late Pleistocene. This abrupt crisis, ending the favourable optimum induced by strong astronomical insolation, was coeval in the Old World with the collapses of the oldest urban societies and civilisations in India, Mesopotamia and Egypt but also in the Mediterranean Basin. Until recent paleoclimatological research and radiocarbon chronology wide use, those collapses had been related by historians to political disorders, nomadic invasions, meteoritic impact (and even… UFOs arrival!) but never to climatic change.

Nowadays, a great number of scientific data point to correlative climatic and societal events, peaking between 4,000 and 3,500 BP, from the Middle East to the western Mediterranean Basin. It is logical that migration waves, famines and political disorders originated from a single major cause : a climatic crisis inducing the quick settling of aridity in formerly well-watered regions where civilisation had developed around irrigation, breeding and urbanisation patterns.

• In the Middle East, precipitation significantly lowers, the formerly perennial wadis become seasonal or totally dry up. The stream levels enter an important incision phase after 4,000 BP, which limits irrigation. Between 3,800 and 3,500 BP, the level of the Dead Sea has lowered by some 100 m ! A major cycle of soil encrusting, aeolian erosion and dust deposition, five times more important than before 4,000 BP, is registered in the geological sections during the same period. Consequently, soon after 4,000 BP, the agricultural and commercial economy of the region collapses and urban civilisations give way to pastoralism. In northeastern Syria, the quick aridification induces between 3,700 and 3,500 BP the collapse of the Akkadian agro-imperialism.

Some historians relate to this climatic change the increase of religious activity which, instead of a needed technological change, was meant to struggle against divine wrath…

• In Turkey, lake Van low levels from 4,100 to 3,000 BP are matched by an abrupt doubling of aeolian sedimentation by 4,200-4,000 BP. At Konya, the drought begins between 5,000 and 4,500 BP. In the South-East, monsoons begin to weaken by 4,300 BP. A change of sedimentation affects the whole Aegean coastal plains around 4,300 BP and in the whole Aegean area, a wave of urban collapse peaks at 3,800 BP.

• To the north, the climate becomes drier and hotter as soon as 4,500 BP. The climatic change affects Ukraine where a strong aridification takes place between 4,100 and 3,500 BP. Agricultural communities collapse and are replaced by nomadic cultures.

• To the east, even the rich "Eden" between the Tigris and Euphrates (Mesopotamia) becomes more arid and crops widely suffer. The cereal production, given at 1,700 kg/ha at 3,800 BP, has lowered to 990 kg/ha in 3,600 BP and at 600 kg/ha only in 2,700 BP, after the end of the dry spell. The rich Indus valley sites of the Harappan culture are also abandoned by 3,600-3,500 BP.

• To the west, in Italy, a reduction of arboreal pollen is shown at 3,700 BP, rivers and lakes suffer from drought until 2,500 BP. The widespread abandonment of settlements and population migrations from the eastern and southern Mediterranean may be one of the reasons for the dynamic cultural phase in Iberia.

• In the north of Africa, around 3,700 BP, the Nile discharge is reduced, aeolian processes are strong, lake levels are low, even the Nile Delta suffers some degradation, arboreal vegetation disappears and the Egyptian centralised government collapses. The climatic curve reflecting Holocene changes from the Atlantic to the Red Sea applies everywhere in the area. The Mediterranean rainfall retracts northwards, the Early and Mid Holocene habitable areas abruptly return to aridity between 4,000 and 3,000 BP and, as everywhere in the northern and western peripheries of the Mediterranean, sedentary life gives way to semi-nomadism, due to a break in the irrigation – agriculture and breeding systems. The semi-sedentary populations in the Saharan basins migrate towards refuge areas that is the large rivers (Nile, Senegal) and the Atlantic coast where large game and fresh water are still available. Up to modern times, nomads or semi-nomads will prevail in the whole area (see Fig. 2).
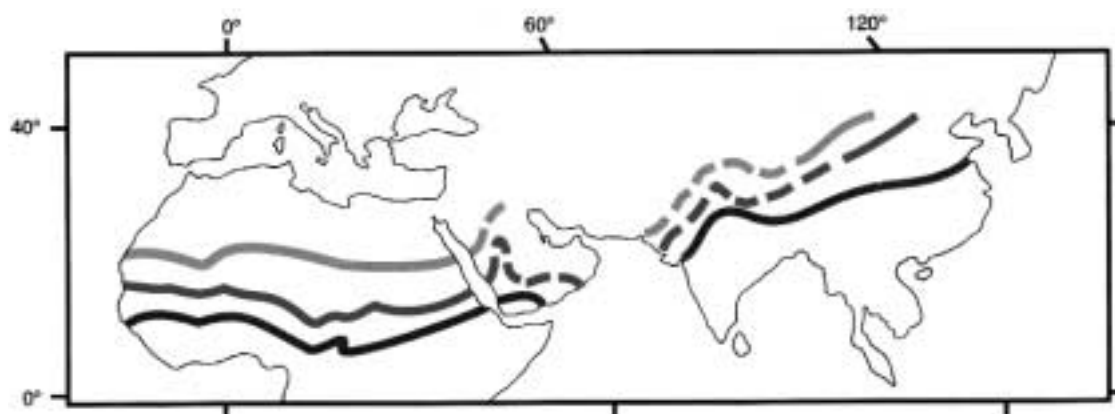
Fig. 2.   EXTREME CLIMATIC CHANGES OVER THE LAST 20 KA

Monsoonal range: ▬▬ Present   ▬▬ Last Glacial Maximum   ▬▬ Holocene Optimum

Therefore, from ca. 4,000 to ca. 3,000 BP, with a peak around 3,700 BP, synchronous civilisation collapses take place, from the Aegean world to India, correlative of the climatic change, observed in the extant arid and semi-arid areas, from the Atlantic to Tibet.

CONCLUSIONS

A natural global warming followed the insolation maximum at the end of the Pleistocene. The former glacial dry phase had induced a reduction in the strength and range of the monsoons and of the coupled Mediterraneans depressions. The interglacial phase beginning around 10,000 BP did in contrast stimulate them, implying a precipitation increase over the Mediterranean, the North of Africa and the Middle East.

Man was sensitive to these large-scale climatic changes, either benefiting from extended migration possibilities, reduced insularism and continental surface extension (during the glacial sea level lowering) or benefiting from a favourable water-budget (during the subsequent optimum). When population had grown and urban cultures had developed, a new climatic change destroyed the civilisation patterns based upon former climatic conditions by ruining food production, commerce and the urban life styles. *The denser the population, the more elaborate the networks of socio-economic and geopolitical structures, and therefore the greater sensitivity of man to climatic change.*

Our natural, astronomical climatic future is towards a new glacial after some 50,000 years stability, however, during the last decades, the generalisation of climatic anomalies (cyclones, storms, floods…) and the 0.7° C increase of the planet's surface temperature, the melting of sea ice and of mountain glaciers (Fig. 3), attributable to the enhancement of the natural greenhouse effect due to atmospheric pollution, *indicate a disruption of the climatic physical balance.* The expected warming during this century should widely outrange the natural variability observed in
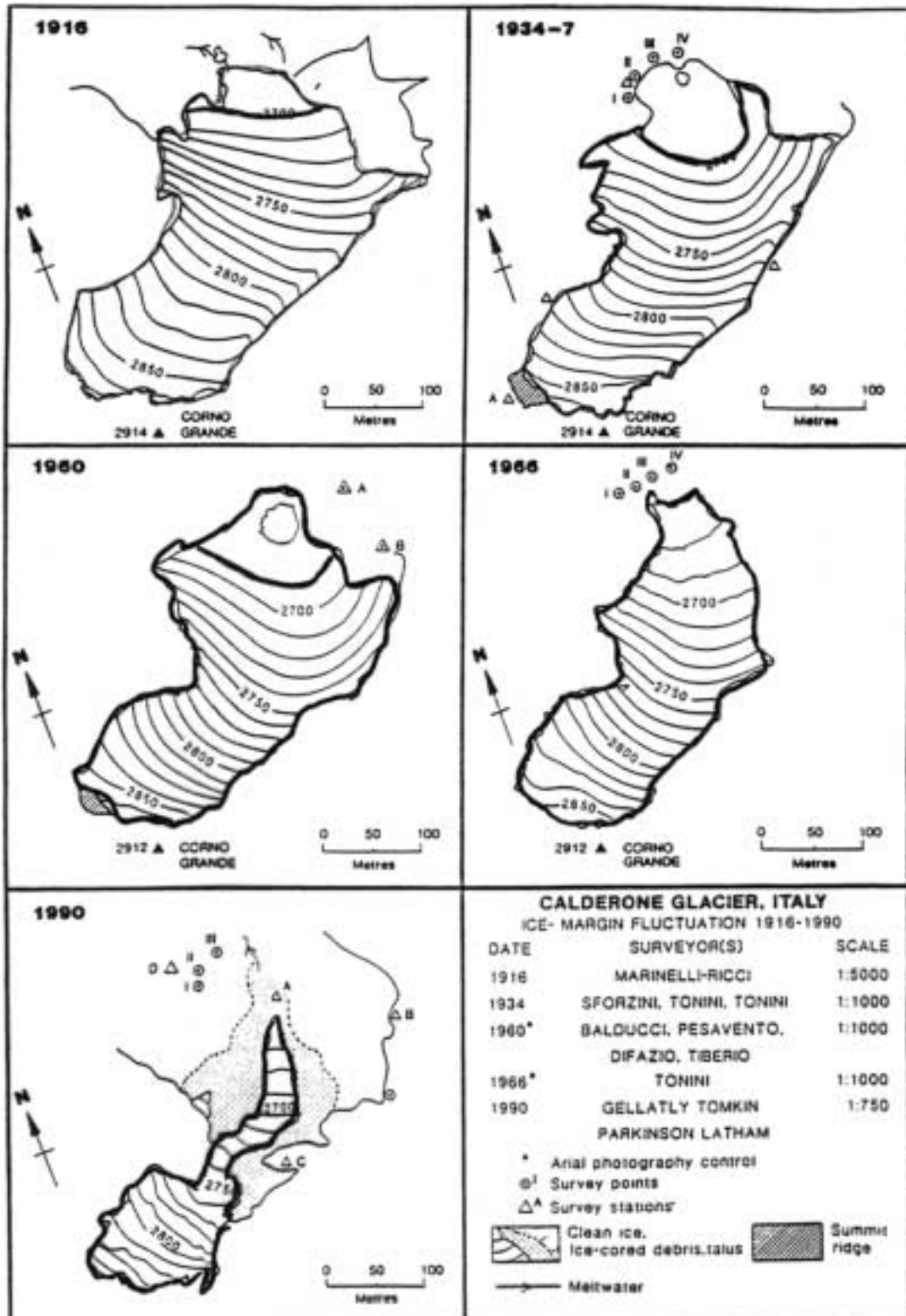
Fig. 3.

the past 2,500 years. The physicists predict, within a few decades, an increase of aridity in the Mediterranean area and a sea level rise ranging from 50 cm to 80 cm, which could hit several low areas, such as deltas.

At the same time, the globalisation of our economic systems and food production – killing local and even regional former economies – utterly fragilises humanity.

Forgetting some proud and naive optimistic views, we have to modify quickly our thoughts and habits. What public opinion… and governments, commonly thought to be stable is in fact highly changeable. *Our economic systems, energy services, production modes, transportation means, health problems, social organisation, common and individual life styles are concerned by climatic change which even our most advanced technologies cannot master.*

A vital challenge is in front of us : how to cope with the beginning crisis ? How to prevent its further increase by other than political resolutions which nobody follows ? or, simply, how to live with it within a few decades ?

Adaptation of our complicated life networks will prove difficult. It implies a complete and quick change in our philosophy of life. Shall we be wise enough to insure the survival of our civilisation ? Mediterranean populations may have a better horizon in front of them : since many of them still keep a little changed traditional life style, out of the large urbanised areas, they may better adapt to the coming regional temperature rise and droughts predicted by climatologists. Indeed the unusually hot 2003 summer induced less casualties in southern France than in more northern areas.

Evolution of Nile deposits input during the quaternary and its effect on Egyptian coastline

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The birth of Mediterranean civilizations might be correlated to the environmental and climatic conditions favorable for man to settle. The study of the Holocene, which started at about 10000 BC, and prehistoric eras is of utmost importance to understand the past, manage and control the present coastal zone and to forecast the future global climatic and environmental changes. The archaeological remains and the historical and geological records are the main helpful sources to understand the paleo-climatic and environmental conditions.

HISTORY OF NILE DELTA

According to De Heinzelin (1968), the course of the present Nile as a continuous river, from Uganda to the Mediterranean, was not established until geologically very recent times. This was preceded by the proto-Nile, which drained Egypt, northern Sudan and eastern desert, possibly sometimes reached the Red Sea. C14 dating by Butzer and Hansen (1968), Said *et al.* (1970) and Butzer (1971), indicated that a flood regime of Ethiopian origin operated in the Nile at least 50,000 years ago. During the early and middle Pleistocene (1,000,000- 100,000 years ago), Nile flood was mainly during winter. During the late Pleistocene and Holocene, this alteration continued but periods of greater floods were paralleled by greater rainfall in Ethiopia. Consequently Nile floods were higher and faster, carrying coarser detritus than today. The stratigraphical and dating of the Holocene sediments indicate that the moist periods lasted 2,000- 3,000 years and the hyper-aridity about 1,000 years each. This cycle period is similar to the cycles recorded in the north Atlantic. Similar to other deltas, the Nile delta is presently subjected to significant coastal changes because of reduction in the Nile discharge and sediment load to the Nile promontory mouths following the construction of water control structures and dams along the Nile. Since building of the High Aswan Dam in 1964, sediment discharge at the Nile promontories has reduced to near zero. This is accompanied by the historical fluctuation in the Nile floods due to changes in climate over the Nile basin in the equatorial east Africa (Stanley and Warne, 1993). In the absence of sediment supply to the coast, the continued action of waves and currents act together with the relative rise in sea level to induce beach changes. Sediment input to coastal waters has fallen by around 160 million t y^{-1} (Entec, 1999). The erosion pattern is complex, with specific areas experiencing significant erosion, with the resultant material being transported to adjacent areas that consequently undergo significant accretion.

Generally, Quaternary subsurface stratigraphy of Nile delta coastal plain consists of, from bottom to top: alluvial sand and stiff mud (older than ~12,000) uncomfortably overlain by shallow marine to coastal transgressive sand (~12,000 to 8,000). This sand is, in turn, unconformably

overlain by a variable sequence of Holocene deltaic sand, silt, and mud as old as ~7,500 yr (Stanley and Warne, 1998). The sedimentary sequences consist of wide varieties of deltaic and marine Quaternary sediments. They are related to the Neonile depositional phase, which started 30,000 years ago (Said, 1981).

Analyses of boreholes (Attia, 1954), in the south Mediterranean in front of the Nile Delta show important features: Offshore holes, at about 20-30 km in the sea from Rosetta and Baltim (Damietta), have continental sediments at the top for a thickness 120-200 m, with lignite peat layers. The Pleistocene to Pliocene sediments underneath are of marine origin. This indicated that in the late Pleistocene the Nile Delta was more extended northward by 30 km at least from the present coast and a number of Nile branches were debouching to the east or the west. The sands of the Pleistocene formation are generally coarser than that in the present Nile.

The vertical motion of land, subsidence or emergence refers to the lowering or emerging of the land surface relative to a geodetic datum. Vertical motion varies locally depending upon rates of isostasy, tectonism, compaction anthropogenic influences (groundwater or oil withdrawal) from combination thereof. Subsidence and emergence is generally independent of world (euostatic) sea-level changes. Based on age-dated sediment core sections, Stanley (1988), Stanley (1990) and Stanley and Warne (1993) have estimated long-term average subsidence rates across the Nile delta region. Subsidence has been considerably lower in a westerly direction, ranging from 5mm/yr at Port Said in the east to ~1mm/yr farther to the west from Alexandria region.

We must know how the coast developed, the age of certain prominent features (lakes, Nile mouths), the periods and rate of their retreat and advance. Knowledge of the geological structure is necessary to evaluate how shoreline erosion may be due to recent sea level rise and land subsidence.

The valley and delta troughs of the Nile offered the only environment in Egypt that favored the accumulation and preservation of sediment during the Quaternary, which was an epoch of intensive erosion. In spite of the fact that the Nile has a very small discharge (86 billion m^3/y) compared to other major rivers as: Amazon (3,000), Congo (1,400), Zambezi (500) and Niger (180), it plays an important role in the life of Egypt (Said, 1981). Flowing midway through the rainless wastes of the desert of Egypt, the Nile provides it with 98% of water supply. The present Nile is not only small relative to its predecessors. The field mapping of the fluviatile and associated sediments of the Nile valley and the examination of a large number of boreholes both deep and shallow show that it is possible to conceive of the Nile as having passed through five main episodes since the valley was cut down in late Miocene time. Each of these episodes was characterized by a master river system. Toward the end of each of the first four episodes the river seems to have declined or ceased entirely to flow into Egypt These five rivers are termed by Said (1981) Eonile, Paleonile, Protonile, Prenile and Neonile. The Eonile was a late Miocene feature, which was responsible for the cutting of the modern valley to great depths. The depth of the Eonile canyon in northern Egypt reaches about 2,500 m. No deposits of the Eonile system are known in outcrop since the river was dredging its bed to the new lowered base level of the desiccated Mediterranean. The sediments belonging to the Paleonile consist of a long series of interbedded, red brown fluviatile to fluviomarine clays and thin, fine-grained sand silt lamina, which crop out along the banks of the valley and many of the wadies which drain into it. The recognition of the deposits of the succeeding three rivers makes possible the division of the Pleistocene of the Nile into a threefold system. The deposits of each are distinct in lithology, stratigraphical relationship and mineral content. They are separated from one another by great unconformities and long periods of recession. The Protonile, was a highly competent river that carried cobble and gravel-sized sediments made up mainly of quartz and quartzite. The deposits of the Prenile are mainly made up of massive cross-bedded sands. The deposits of the Neonile, which is still extant, are indistinguishable from those of the present day river.

NATURE OF SEDIMENTS

The coastal zone has a minimum width in the west of the Nile delta, where the sea attacks the Miocene limestone which form a wave-cut cliff, to several tens of km in the east, where a wide coastal plain and a narrower piedmont plain can be differentiated. To the west of Alexandria the

coastal strip is bordered by the Nile flood plain. Philip (1953) divided this area into four zones according to the geomorphology and the nature of sediments:

1- the Rosetta – Abuqir zone. The coastal zone is shaped by terrestrial depositional agencies where the Nile contributed great amounts of materials. However, erosional elements of the sea and the wind have taken a part in shaping the landscape, a role that has increased since the construction of the High Dam. The sediments in the beach zone are grayish in color being mixed with Nile silt, the amount of which decreases to the west. Shells and shell fragments may constitute up to 20% of the beach sediments.

2- Abuqir – Dekheila zone. The coast exhibits features of a youthful shoreline primarily shaped by marine erosion. Wave cut cliffs border it at many localities and can be seen in places where man does not modify the original picture. Small bays separated by points, islets and stacks characterize the coast. Islets frequently shelter the bays from the open sea and may be joined to the land by a wave-cut bench. The shore zone is essentially narrow, with yellowish sands, mixed to a smaller extent with Nile silt than in the first zone. Shell fragments may make up to 10% of the total sediments.

3- Dekheila- Sallum zone. Three geomorphic units could be distinguished: the coastal plain and the piedmont plain of Pleistocene and recent sediments, and the Plateau or table-land of Miocene limestone, the northern edge of which forms an escarpment running mainly E-W and rising 50-75m above the piedmont plain. Consequent streams that flow northward to the sea dissect the plateau; these are mostly dry at the present day time. The plateau is structural and represents the northern extremity of the Homoclinal Plateau that covers much of the western desert between the Qattara Depression and the Mediterranean Sea

4- The zone extending from Sallum westwards. A 100 m high wave-cut cliff of Miocene and Pliocene rocks closely borders the beach. Comparatively large consequent streams cut the cliff. At many localities the sea inundated the valley floors indicating submergence. The strata are in places very disturbed, due apparently to slumping.

The submarine morphology does not warrant a classification of the Nile continental shelf as a featureless flat deltaic area, mantled over by the discharge of Rosetta and Damietta mouths. Only these two cones appear to be in genetic relation, morphologically, to the two main distributaries. They appear to cut across features of earlier formation, the upper terraces and some of the continuous slope breaks. Further, the lower terraces are geographically extensive surfaces, which are covered by Nile mud only in part, mostly being covered by bioclastic debris. In conclusion, the topography of the continental shelf of the Nile delta is far from simple, resulting from the interplay and summation of many factors. To mention a few: standstills during the euostatic sea of the bottom, local hydrodynamic effects and recent tectonic activity. The present sediments of the Egyptian Mediterranean shelf, where there is now no further Nile contribution – the only possible source of beach sand (outside the coast itself) – were formed during the Pleistocene - Holocene sea level and by the Nile deposition in the last few thousands years. Therefore, it is important to know the history of these sediments, the rate and the direction of the accumulation of the recent Nile deposits. At the recent glaciation period, sea level was at least 85- 90 meters below the present at about 30 km north of the present coastline. The subsequent rise was associated with sea level advance and coastal retreat. During this time the Nile sediment contribution was not significant to the advance of the coast, except in the development of the submerged parts of the Nile Delta and to build-up the Nile mouths of which the existing Rosetta and Damietta. The dating of sediments and shoreline features was done by means of fossils (pollen), artifacts and archaeological remains, using C^{14} analysis in organic material (wood, peat and shells). The historical records were also a helpful tool. However archaeological and historical records provide evidence no longer than 2,000 years ago, while C^{14} gives more precise dating.

The main change that occurred on the coast during historical times is the reduction of the Nile mouths from seven or more mouths to only two now existing. The coastal region has also been deteriorated by the formation of marches and lakes following subsidence or other causes. The positions of the different Nile branches have been confirmed by archaeological findings

(Toussoun, 1934). The arrangements of the Nile branches at the XVIIIth dynasty seem to be the same as Vth century B.C. except for two additional branches into lake Maryout. The supply of suspended fluvial sediment pattern to the sea, in the past 20,000 years has been: 20,000-10,000 B.P. (little sediment supplied), 10,000-5,000 B.P. (high sediment yield), 5,000-2,000 B.P. (increasing proportion trapped in deltas), 2,000-300 B.P. (little sediment supplied, chiefly clay and fine silt) and from 300 B.P. to present, high sediment yield and much material stored in deltas. Therefore, the periods of high sediment yield were in the early Holocene and from 300 B.P. to present. The man-made High Dam in the south of Egypt drastically affects sediment supply in the south east of the Mediterranean.The sea level rise for the last 3,000 years has been less than 1 m in the last 100 years the rise is estimated at between 1 to 1.4 mm/year (Arab Republic of Egypt, 1973).

The Holocene sea level curve of the Israeli coast

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The sea level curve of the Mediterranean coast of Israel over the last 9000 years is a product of three different research projects. Two of these projects are based on archaeological indicators for sea level, while the third is based on bio-constructions.

The curve is based mainly on archaeological data. Most of the observations used are from submerged archaeological sites, with a few land observations of water-front man-made structures and wells located up to 100 m from the coastline. These archaeological data bracket the upper and lower limits of any change.

The submerged Pre-Pottery Neolithic settlements (the oldest age obtained varies between 9270 to 8770 cal years BP) up to the Chalcolithic sites at about 6500 cal BP are always found embedded in dark clay. In contrast, shipwreck assemblages from Middle and late Bronze age to the Hellenistic period, ~4000 to ~2100 years ago lie above the clay layer all covered by sand. The submerged prehistoric sites, as well as younger remains of man-made structures and shipwrecks, suggest that a rapidly rising sea advanced over the coastal shelf, covered and flooded prehistorical settlements and buried the sites under sand.

We use archaeological data as constraints on paleo sea levels and we then compare the observational limits with hydro-isostatic models for sea-level change across the region. Differences, if significant, between the observed and predicted change are interpreted as being of tectonic origin.

The ice models used include contributions from Fennoscandia, the Barents Sea, Laurentia and Antarctica. Their combined volume includes a small increase in ocean volume for the past 6000 years due to residual melting of distant ice sheets, possibly from Antarctica or possibly from temperate mountain glaciers such that sea-level has risen globally by 3 m since that time.

For the eastern Mediterranean, the hydro-isostatic contribution is one of falling sea level along the Israeli coast in response to the loading of the Mediterranean by the melt water and the flow of material from beneath the oceanic lithosphere to beneath the continental lithosphere, but the final predicted sea level is one of a slowly rising level throughout the past 6000 years since the small increase in ocean volume was largely sufficient to negate the hydro-isostatic contribution. For the interval for which observational evidence is available, the range of predictions at any time step does not exceed 3 m and is of a similar magnitude or smaller than the observational uncertainties of much of the data.

Both observations and hydro-isostatic models indicate a rapid rise before about 6000 BP with levels predictions at −13.5 ±2 m and observations at −16.5 ±1 m at about 9400 cal BP. Predicted level at about −7 ± 1m are consistent with the archaeological evidence at about 8000 cal years

BP. According to both observations and predictions, sea level was still lower than –3 to –4.5 m at 6000 BP and remained below its present level until about 2000 BP (Sivan *et al.*, 2001). Sea levels at –20 m and –7 m along the continental shelf of Israel imply coastlines at about 1.5 and 0.5 km off the present one respectively.

The archaeological observations and the model sea-level curve along the Mediterranean coast of Israel were found to be generally consistent. The typical magnitude of the observational accuracies is about ±2 m. Agreement between the observed and the predicted estimates is broadly satisfactory and any discrepancies generally lie within the combined uncertainties of the observations and predictions (see Fig. 1 below).
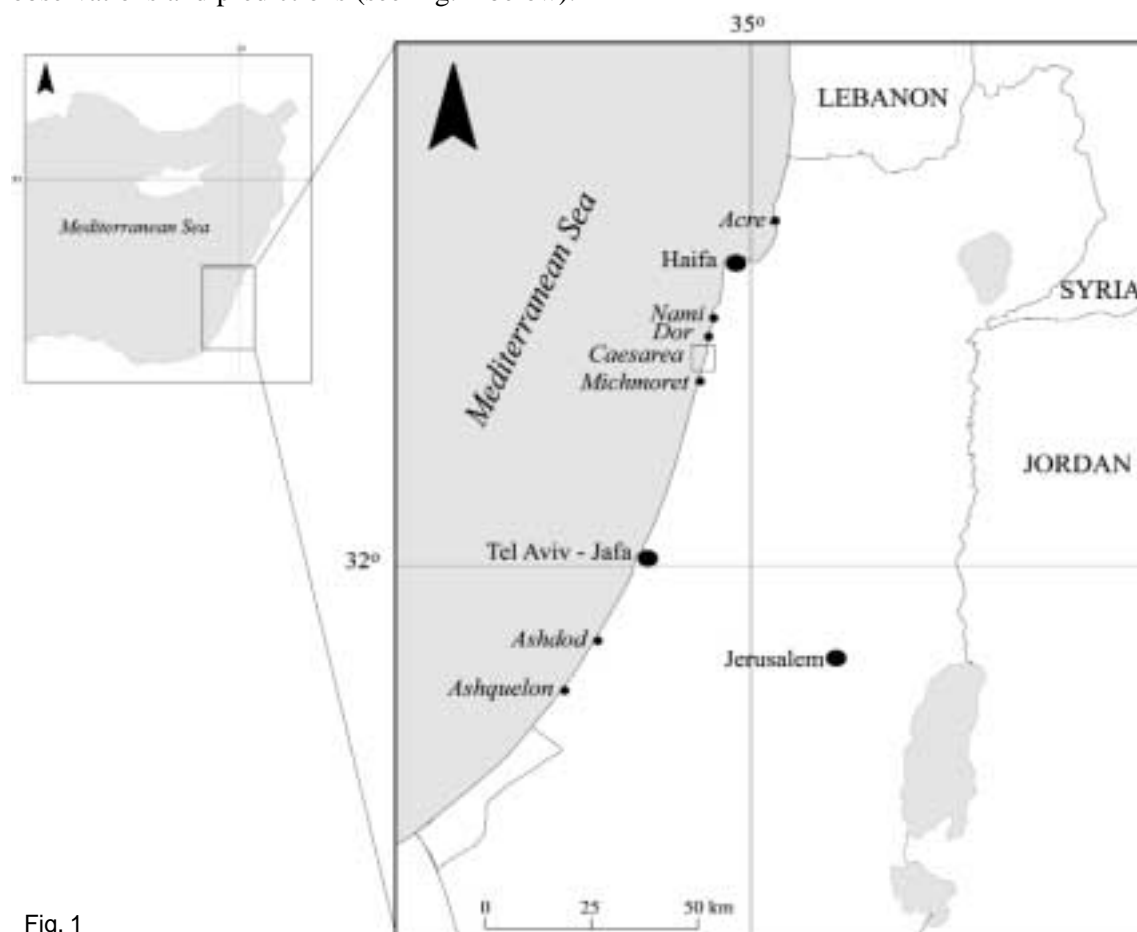
Fig. 1

The comparison also enables to conclude that the average rate of vertical tectonic movement for the last 9000 years, at least along the Carmel coast of Israel has been less than 0.2 mm/y.

Sea-level changes from 2000 to 700 years ago (Early Roman to Crusader periods) are also based on archaeological observations but in this research, the data obtained are only from water wells, of Caesarea, southern Carmel coast. Caesarea has had nearly 1300 years of continuous occupation during which many wells were dug. The major construction at the site took place under King Herod of Judea between 22 and 10 BC. During the detailed excavations of ancient Caesarea, 64 coastal wells have been examined that date from the early Roman period (with the oldest occurring in the 1st century AD), up to the end of the Crusader period (mid 13th century AD). Such a large number of reliably dated wells within an excavated area of about 0.5 km², and spanning a time interval of about 1300 years, provides a high-density, high-resolution, database for establishing sea level along this section of the coast once the relation between the water table and sea level is known.

The present-day measurements carried out as part of the research, in two domestic Roman wells indicate that the present water table occurs on average about ~0.5- 0.6 m above MSL, varies up to +0.6 m and but occassionally reaches +0.7 to +0.8 m above MSL. Seasonal variations in

mean sea level demonstrate winter levels at about 10 cm above the average level. Therefore, based on our working hypothesis that a functioning well must contain at least 30-40 cm of water under all conditions as the minimum water column required to secure an effective draw of water with the jars used at the time of well construction, we adopt +0.8 ± 0.14m as the offset between the water table and the annual MSL. The equation used was well bottom plus 30 cm representing minimum past water table, and this past water table minus 80 cm indicating palaeo sea level.

The inferred time series for sea level changes based on this equation indicate that from 2000 BP (the early Roman period, 1st century AD) to about 700 Bp (Crusader period, 12th to 13th century AD) sea level ranged between 30 cm higher than today at the Byzantine period (4th to 7th century AD) to 20 cm lower than today at the Crusader period. The accuracy of this sea level reconstruction is ± 20 cm.

Comparison of the Caesarea water well observations with predictions based on models of glacio-hydro isostasy yield a satisfactory agreement within the range of uncertainties of both data sets. The well data are also consistent with an absence of significant vertical tectonic movement of the coast at Caesarea over about 2000 years. Convincing evidence of the neotectonic stability of the coastal plain of Caesarea is provided by the water supply system of the city, which included raised aqueducts. The high aqueducts are approximately 7 km long. The aqueduct system consists of two parallel channels, the left is dated to the Herodian period about 10 AD, while the right was built in 130-135 AD by the legions of the Roman emperor Hadrian. In spite of its age, the present average gradient has remained unchanged at 0.04%.

The near-coastal well data from Caesarea appear to provide reliable indicators of sea-level change for a period beyond the reach of the instrumental data and when most geological data are of lower accuracy.

Sea levels for the last 700 hundred years is based on bio-structural indicators. The research is still an on-going research in which so far only two preliminary ages were obtained for the contact between the abrasion platform (kurkar) and the vermetide reef of *Dendropoma*. We assume that the base of the *Dendropoma* reef reflects ± sea level at the time of its initiation. Therefore, it seems that sea level reached its present level ± 10-20 cm at mid 15th century AD. (see Fig. 2)

Palaeogeography changes along the coast during the inferred periods

The Israeli shelf and coast have witnessed significant changes started at 9000 years BP when sea level was at about –20 m, the Mediterranean shelf was partly exposed, and most of the coast now covered by sand was a wetland area. Since then, the sea level has risen and the climate has
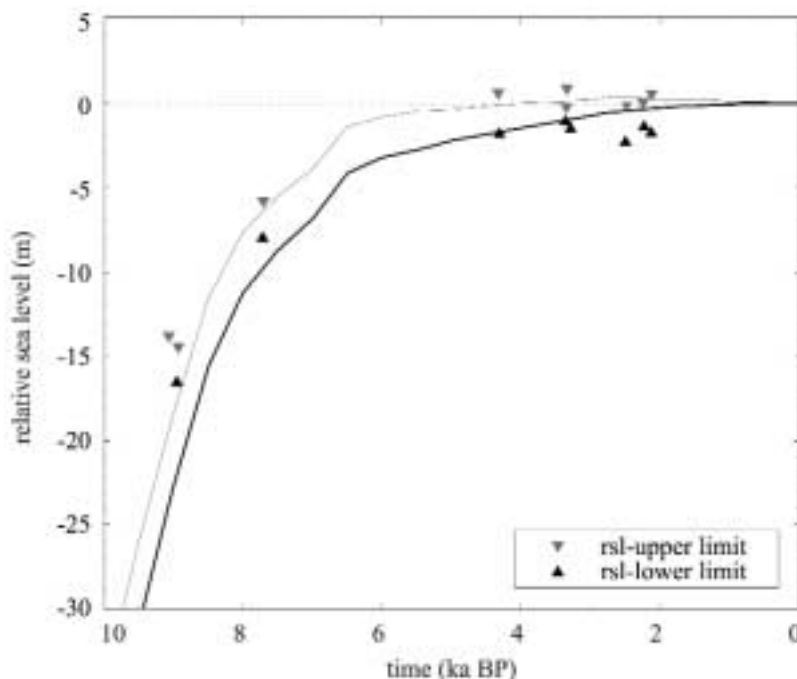

Fig. 2

undergone significant changes, which create varying geomorphological changes. Initially, marshes were created, the coastline changed its morphology, and over the last few thousand years, sands started to accumulate. As a result, the stratigraphic sequence along the coast consists of sands unconformably overlying dark clays that were deposited in wetlands, with the dark clay unit becoming reddish-brown paleosol at the bottom (Sivan *et al.*, in press). This sequence of sands, clays and paleosol overlies the irregular topography of the Late Pleistocene upper calcareous sandstone (locally named kurkar), The shelf and the coast consist of longitudinal kurkar ridges and troughs between them. The clays which were unconformaby deposited in the wetlands on the kurkar and /or on the paleosol at the troughs are mainly Holocene in age. In the coastal trough, now covered by sand, the swamps at Dor, southern coastal plain, originated between 12,240 cal BP and 10,820 cal BP (Sivan *et al.*, in press), while at Ma'agan Michael, few km south of Dor, they were originated at about 11,000 cal BP (Cohen-Sefer, pers. comm.). From the peak of the LGM, the sea level rose relatively quickly but was at about –75 m at 12,500 BP (Fairbanks, 1989; Lambeck and Chappell, 2001). These marshes dried out at Dor area between 8940 cal BP and 7860 cal BP according to the ages obtained from three cores (Sivan *et al.*, in press), at 9550 cal BP according to Kadosh *(*pers. comm.) and at about 9000 cal BP in Ma'agan Michael (Cohen-Sefer, pers. comm.). Sea level between 9500 BP and 8000 BP was still low as mentioned above, and the coastline far to the west. The sediments, both at Dor and at Ma'agan Michael, contain foraminifera, ostracodes, and mollusks (bivalves and gastropods). Most of the well-preserved species indicate low to brackish water salinity (Sivan *et al.*, in press). Palynological research carried out in one core at the area of Dor suggests fluctuations in humidity between 10,250 and 9,550 cal BP, with precipitation higher than today based on pollen grains of trees, which do not grow in the area today. These grains also indicate slightly lower temperatures at the time of their deposition.

It seems that the origin and the existence of the wetlands, at least at the coastal zone of the Carmel coast of Israel, have a stronger connection to climate changes, than to sea level changes, during the aforementioned period. The ages obtained so far, do not allow precise correlation to high-resolution global climate events. Nevertheless, it can be concluded that in general the origin and existence of the marshes occurred from the extreme dry conditions of the LGM to the maximum humidity relating to the Holocene Maximum. The termination of the marshes may be related mainly to global drying events and only indirectly to sea level changes.

Human settlement started at the Carmel coast on top of the dark clay unit shortly after the drying up of the coastal marshes, during the Pre-Pottery Neolithic period. Later, during the Neolithic - Chalcolithic periods, the sites along the Carmel coast were all settled, also on top of the dry dark clay. Only during the Middle Bronze IIA, at about 4000 BP, when the sea level rose to about –1m to –2 m, did people start to settle on the kurkar hills along the coast. Most of the marshes east to the kurkar ridge still existed during all these settlement periods, up to the 20th century. The sands started to accumulate in the area at about 4,500-5,000 BP. Most of the sands along the Israeli coast are even younger than 4000 years. The sea reached its present level in the last 2000-3000 years, carrying more sands that cover the coastal clays and creating the relatively smooth present-day coastline.

Conclusions

• Holocene sea levels rose along the coast of Israel from about –20 m at about 9000 cal years BP to about –7 m at about 8000 cal years BP and remain lower than today up to about 3000 BP.

• There are no indications for Holocene high stands along the Israeli coast, neither from observations nor from the isostatic model.

• Up to 7000 cal years BP, the coastline is still far to the west up to 0.5-1 km seaward.

• During the Younger Dryas and the beginning of the Holocene, wetlands prevailed along the coastal trough in between the kurkar ridges. Most of these coastal wetlands are now covered by sand. These marshes were fresh water to brackish. Between 9000 to 8000 cal BP these marshes dried up. Sea level at that time was still lower than today and the coastline far offshore.

• Submerged prehistoric sites, from Pre-Pottery Neolithic to Chalcolithic period, were found on the dark clay previously deposited in the wetlands. Sands that started to accumulate only around 4500-5000 years ago, when sea level was only 1-2 m below present one, had covered these sites.

Holocene coastal changes in the Acheloos alluvial plain (northwestern Greece) and their effects on the ancient site of Oiniadai

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Holocene coastal sediments are valuable geoarchives for the reconstruction of past landscapes and their changes through space and time (cf. Brückner *et al.,* 2002; Brückner 2003a, 2003b; see also Brückner *et al.*, this volume). The Acheloos alluvial plain is situated in the westernmost part of the Greek mainland. It is the largest plain along the coast of the Ionian Sea and therefore of decisive importance for the understanding of Holocene changes in this area. Oiniadai, an ancient site in the southern part of the plain, was famous for its shipsheds of the 3rd century B.C.. Due to siltation processes caused by the progradation of the Acheloos delta, it lost its function as an important harbour site (see also Sakellariou and Lykousis, this volume). Nowadays Oiniadai lies some 9 km distant from the open sea.

The results presented herein are part of a paleogeographical-geomorphological study dealing with the whole Akarnanian coast as well as adjacent regions. The main objectives are to find out more about the causes of Holocene environmental changes and their local to regional characteristics. Eustatic sea level rise, the neotectonic setting, sedimentological factors such as subsidence, and anthropogenic influences all will be taken into consideration.

Sediment core profiles document lateral as well as vertical environmental changes, and serve as the basis on which spatial and chronological scenarios can be built up. The model used is Johannes Walther's "law of correlation of facies" from 1894 (Middleton, 1973, quoted in Kraft and Chrzastowski, 1985: 636).

To find out more about the Holocene genesis of the Acheloos alluvial plain, the following questions must be answered: (i) Was there a typical delta evolution in a classical sense? (ii) What was the sedimentological role played by the former Echinades islands which are today joined to the mainland by sediment? (iii) What scenarios can be developed for the siltation history of the area?

GEOLOGY AND TECTONICS OF AKARNANIA

The Acheloos alluvial plain lies southeast of the Akarnanian mountains which are the southern continuation of the Epirus mountains. Both ranges belong to the western Hellenic nappe of the Ionian zone of the Hellenides. The sedimentary cover is made up of a sequence of evaporites with a thickness of ca. 3.5 km, followed by a 2 km thickness of limestone and dolomite strata (Jacobshagen, 1986). The strike is generally from north to south with NE-SW- and NW-SE-faults due to extensional movements of the Aegean microplate in the back arc basin (Doutsos *et al.*, 1987; Sachpazi *et al.*, 2000; Doutsos and Kokkalas, 2001). Most of the grabens and half-grabens are filled with younger flysch-sediments (up to 600 m thickness) of the Ionian zone. Where these intersect the coast, they are responsible for the existence of the few coastal plains of Akarnania (Philippson, 1958, see Fig. 1). The tectonic setting of the region is dominated by the nearby boundary between the Aegean and the Adriatic microplate. South of the Cephalonia transform fault there is evidence of the first plate being subducted under the latter (McKenzie, 1978; Laigle *et al.*, 2002). The Katouna fault separates the Akarnanian mountains from their hinterland; from here, Akarnania is moving 5 mm per year faster to the southwest than the central mainland (Cocard *et al.* 1999; Haslinger *et al.*, 1999) and therefore actively pushes the overriding plate (Sachpazi *et al.*, 2000). The tectonic dynamic is the reason for the high seismic activity of Akarnania and the adjacent Ionian islands (Papazachos and Comninakis 1971: Fig. 7; Scordilis *et al.*, 1985: Fig. 1; see also Morhange and Pirazzoli, this volume). Additionally, there are studies which show the geomorphological and neotectonic influence of karst processes within the Triassic evaporites (Philippson, 1958; Galanopoulos and Ekonomides, 1973).
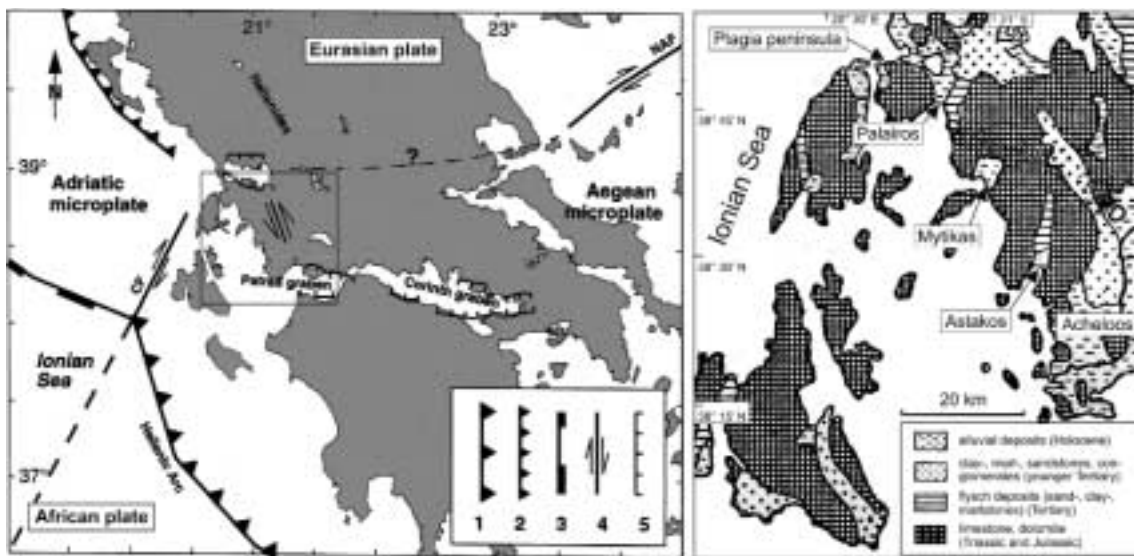

Fig. 1. The Acheloos river alluvial plain within the framework of the tectonic and geological setting of Greece and Akarnania (modified from Vött *et al.*, 2002; base maps from Haslinger *et al.* 1999 and Philippson 1958).
1 subduction, **2** continental collision, **3** Mesozoic passive margin, **4** strike-slip fault, **5** normal fault, **CF** Cephalonia fault, **NAF** western continuation of North Anatolian fault.

THE GENESIS OF THE ACHELOOS ALLUVIAL PLAIN

Neumann and Partsch (1885), referring to ancient writers such as Herodotus and Thukydides (both 5th century B.C.), were the first geomorphologists point out the role of the former Echinades islands, the arrangement of which had accelerated siltation of the marine embayments. Philippson (1958) who undertook his first travels to Akarnania in the end of the 19th century gave his account of a large inaccessible swamp area north of Oiniadai, called the swamps of Lesini. In his opinion they were the relics of the ancient lagoon Melite reported by Strabo. The ancient harbour of Oiniadai, according to Philippson, was connected to the sea via the Acheloos river. Philippson emphasized that the Acheloos area represents a mountain range drowned by sediments rather than a typical deltaic environment. As the distance from Oiniadai to the mouth of the river

Acheloos given by Strabo (70 stadia = ca. 12.95 km) is still correct, he argued that the tremendous shifting of the coastline was already completed by the time of Strabo's account. Based on multitemporal remote sensing data and geomorphological studies, Piper and Panagos (1981) found three systems of abandoned river channels south and east of the modern river. According to their study, sea level rose rapidly until 5,000 B.P., then showed a weak decline at about 3,500 BP before rising again during the last 3,000 years (cf. Kelletat, 1975). Apart from just a few changes in the area of the actual river mouth, they concluded that for the last 2,300 years there had not been any larger environmental change. Furthermore, they reported that a subsidence rate of approx. 0.5 mm per year was responsible for the existence of today's lagoonal systems. Villas (1984) was the first who undertook systematic sediment cores in the alluvial plain. Her scenario suggests that deltaic sedimentation began approx. 5,700 B.P. to the southeast into the lagoon of Etoliko (Villas, 1984: Fig. 33; cf. Stanley and Warne, 1994: Tab. 1). Later, the river sedimentation became focused more towards the southwest and west. In her opinion around 500 B.P. the lagoon north of Oiniadai would have changed into a freshwater marsh. As a historian, Freitag (1994) studied ancient written sources and – in contrast to Philippson (1958) and others – concluded that Melite, compared to the former swamps of Lesini, must have been a freshwater lake situated on the opposite side of the Acheloos river. Fouache's geoarchaeological studies (1999) support the idea that Oiniadai with its shipsheds had a direct connection to the sea and that the Acheloos river was not directly responsible for the siltation of the Lesini swamp area. Finally, similar to the conclusion of Philippson (1958), Grove and Rackham (2001) emphasized that the last phase of considerable deltaic sedimentation must have taken place before the time of the ancient writers, at the latest during the 5th century B.C., due to an increase in sediment transport or a temporary decrease of subsidence rates.

All the cited studies are exclusively based on the interpretation of written reports, maps and remote sensing data; at the most, Piper and Panagos (1981) undertook some superficial sediment samplings. Only Villas (1984) conducted sedimentary investigations in the third dimension (e.g. sediment cores). Unfortunately, her study and facies interpretations were based on only a few core profiles of insufficient depth to provide a complete picture of the Holocene environmental evolution of the alluvial plain.

METHODS

To find out more about lateral and vertical facies correlation in the Acheloos alluvial plain we carried out several vibracorings up to a depth of 20 m below the surface, using a vibracoring device by Stitz and Atlas Copco for cores with a diameter of 6 cm or smaller. The exact position and elevation of coring locations were obtained by means of a Leica differential GPS. The strata were described sedimentologically on site; the samples taken underwent a detailed geochemical analysis in our laboratory. Dr. M. Handl (Marburg) and M. Besonen (Amherst) were responsible for microfaunal analyses and facies interpretation based on the occurrence of ostracod species assemblages (cf. Handl *et al.*, 1999; Besonen *et al.*, 2003). Absolute age determinations by radiocarbon analysis were arranged by Dr. K. van der Borg (Utrecht). For each sediment core profile we established a database for further descriptive and analytical statistical procedures. Based on linear discriminant analysis we have already developed a new methodological approach to facies interpretation using geochemical data (cf. Vött *et al.*, 2002, 2003a).

THE FORMER SWAMPS OF LESINI

The former swamps of Lesini are located north of Oiniadai and Kounovina, and south of the mountain of Kalubitsa (see Fig. 2). Until now it was unclear how far they once extended to the north. At the beginning of the 20th century they were still characterized by a widespread lake during winter flooding (cf. Lolling 1876/77: 285; Philippson 1958). In 1930 the first amelioration measures were undertaken (Fels 1944). The vibracore transect discussed here runs from the coast north of Kounovina (OIN 5) via the central lowland (OIN 4, 8, 9) to the Acheloos river (OIN 10, see Fig. 2). OIN 8 and OIN 9 show similar profiles so that we concentrate on the description of OIN 9 only.

Fig. 3 illustrates the facies profiles of the above mentioned cores. The vertical arrangement of the profiles corresponds to their altitude relative to modern mean sea level. Currently, only strati-
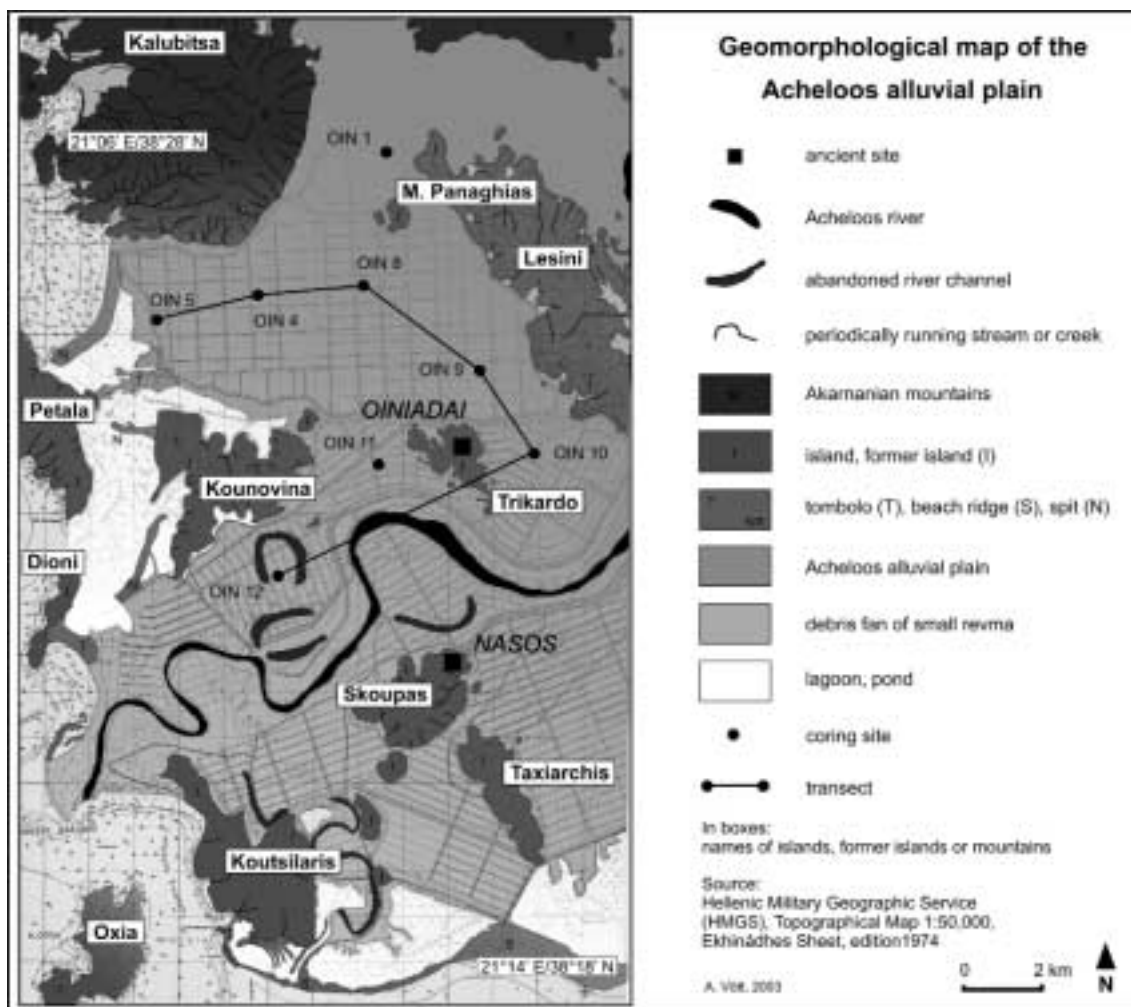
Fig. 2. Geomorphological map of the Acheloos alluvial plain with locations of coring sites and transects.

graphic comparisons are possible as radiocarbon dates are still being processed. Similar sedimentary facies at comparable depths do not necessarily represent synchronous sedimentation; however, they can help to document the lateral arrangement of sedimentary environments. Comparing depths of different strata is bound to the assumptions that (i) there are similar neotectonically induced subsidence rates for all coring sites, (ii) post-ameliorative compaction of sediments is limited to the uppermost parts of the profiles.

The fact that the surface at OIN 4 and OIN 5 lies below the current sea level is caused by the decrease in sediment delivery from the hinterland due to water storage in river barrages for hydroelectric power plants, hydro-ameliorative measures in the Acheloos lowland itself combined with widespread groundwater lowering, and subsidence due to neotectonic processes.

Generally, the profiles show features typical of a marine regression. For the first phase, fully marine environments were detected in vibracores OIN 4, 9, and 10. Provided that they are more or less synchronous, the water depths of the marine embayment must have been deepest somewhere around OIN 4 (see position of marine strata in Fig. 3). The subsequent phase was characterized by the appearance of sediments of a shallow marine environment in the western part of the area at OIN 4 and OIN 5. In core OIN 9 deposits from a fully marine environment were observed up to 8.30 m b.s.l. which means that up to this time there were still open marine conditions at this site. On the contrary, the comparable sediments of OIN 10 are already indicative of a lagoonal environment. This suggests, as a consequence, that a narrow marine embayment must have reached the area from the W or SW, passing over to a lagoonal system in the east. The bay as well as the lagoon were closed off by sandy bars or spits.
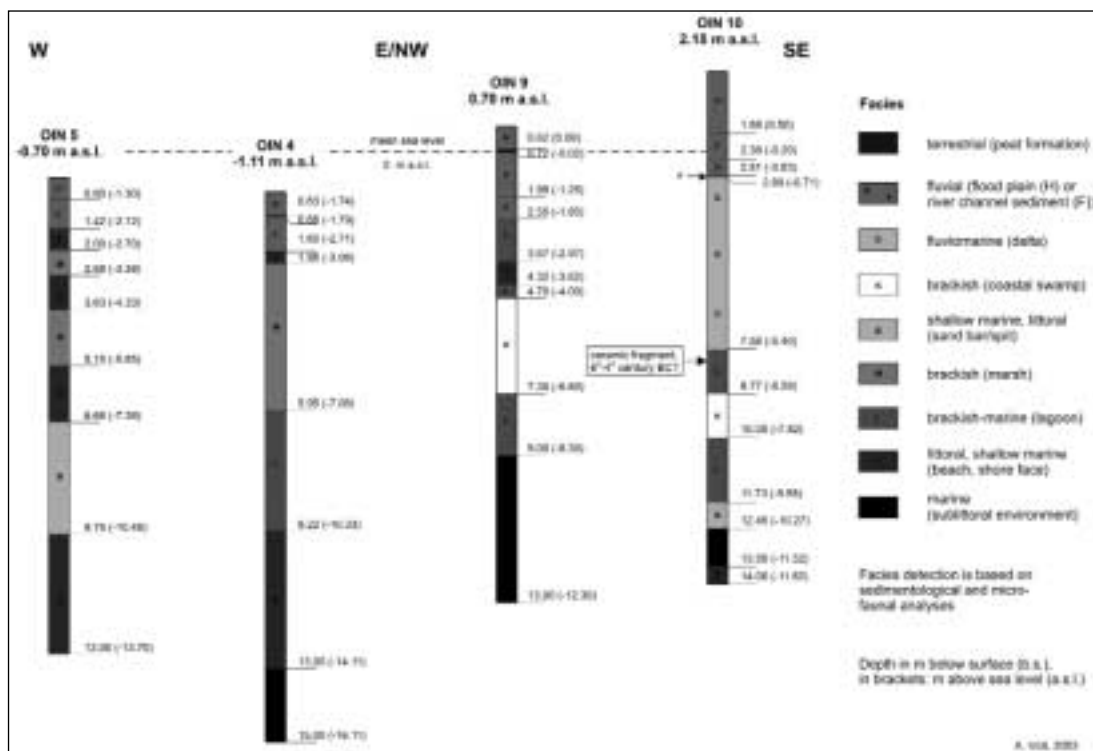
Fig. 3. Summary view of facies profiles for vibracores OIN 5, 4, 9 and 10.

During the third phase the sandy bars in the W reached 5.85 m b.s.l. (see OIN 5 in Fig. 3). Consequently a widespread lagoon came into existence; the sediments of this lagoon were retrieved in cores OIN 4 and OIN 9. As shown by the sediments, the lagoon persisted longest at the site of OIN 9. Sand bar formation east of OIN 10 led to the initiation of a regressive sequence at OIN 10 at an early stage (sandy bar followed by coastal swamp). Assuming that the archaeo-logical dating of the ceramic fragments found in core OIN 10 is correct, lagoonal environmental conditions reappeared along the northern hillside of Oiniadai around the 5th century B.C., where-as siltation of the westernmost part of the lowland had already begun. This is confirmed by marsh deposits found at comparable depths in core OIN 4. Meanwhile, sediments of a coastal swamp environment at OIN 9 indicate the beginning of infilling of the central part of the water bodies from N to S. Passing through of the Acheloos delta next to OIN 10 definitely cuts off the lagoon of Oiniadai; subsequently there is an acceleration of siltation processes at OIN 4, OIN 5, and OIN 9 (marsh sedimentation or coastal swamp formation).

The fourth phase is characterized by two independent marine incursions recorded in core OIN 5 (4.33 - 3.38 m b.s.l., 2.70 - 2.12 m b.s.l.). The sediments of OIN 4 clearly show the influence of the second incursion (3.06 - 2.71 m b.s.l.), whereas the older incursion could only be detected by geochemical analyses (at approx. 3.75 m b.s.l., cf. Vött *et al.*, 2003b). Sedimentary features of OIN 4 and OIN 9 indicate that there still was a narrow bay alongside the hills of Kounovina and Trikardo at the southern margin of the modern plain. We suppose that this area had a consider-able freshwater supply from karstic springs sheltering the remaining bay from rapid siltation. Philippson (1958) reports two springs at the northern flank of Trikardo which, today, are almost dry. In addition, it is striking that at OIN 9 the youngest marine incursion is followed by a lagoon-al environment with sediments that extend up to 1.85 m b.s.l. in the core. This means that the lagoon of Oiniadai was longest lived in the vicinity of OIN 9.

Taking into consideration the transition to fluvial sediments at the presented coring sites, it should be stated that their base decreases from OIN 10 via OIN 9 to OIN 4. Obviously, these sed-iments are due to flooding events of the Acheloos in the eastern part of the area. The compara-tively deep position of the fluvial sediments at OIN 4 may be due to local subsidence connected to modern anthropogenic ameliorative measures.

THE ACHELOOS DELTA *SENSU STRICTO*

The evolution of the Acheloos delta sensu stricto can be revealed comparing vibracores OIN 10 and OIN 12, both of which are strongly influenced by deltaic sedimentation. The facies profile of OIN 10 was already described above; quite similar, OIN 12 reflects the evolution of a shallow marine environment in front of the delta to a delta top marsh. Marsh sedimentation was abruptly terminated by delta sand deposition. Fig. 4 shows the summary view of the two core facies profiles. Due to the fact that the core of OIN 12 is not so deep, fully marine sediments could only be detected at OIN 10; they are free of any direct deltaic influence. Later, close to OIN 10 a sand bar came into existence and initiated the formation of a lagoon. At comparable depths in OIN 12 shallow marine conditions still exist (lagoon at OIN 10: 9.55 - 7.82 m b.s.l., shallow marine environment at OIN 12: 10.40 - 8.29 m b.s.l.). This evolution was due to the Acheloos delta prograding from the NE to the SW.

A later phase was characterized by coastal swamp deposits at OIN 10, followed by a second lagoon which, according to the ceramic fragment found at 7.90 below surface (5.72 m b.s.l.), can probably be dated to the period between the 6th and the 4th century B.C.. Marsh and deltaic sand sedimentation dominate OIN 12 at comparable depths. This seems to support the idea that the late lagoon of Oiniadai reached the Lesini area from the W – north of Kounovina – and did not touch the area around OIN 12. Since core profile OIN 11 (see Fig. 2) shows lagoonal sediments at a corresponding depth, this lagoon might have had a short secondary branch bordering the southwestern flank of Trikardo.
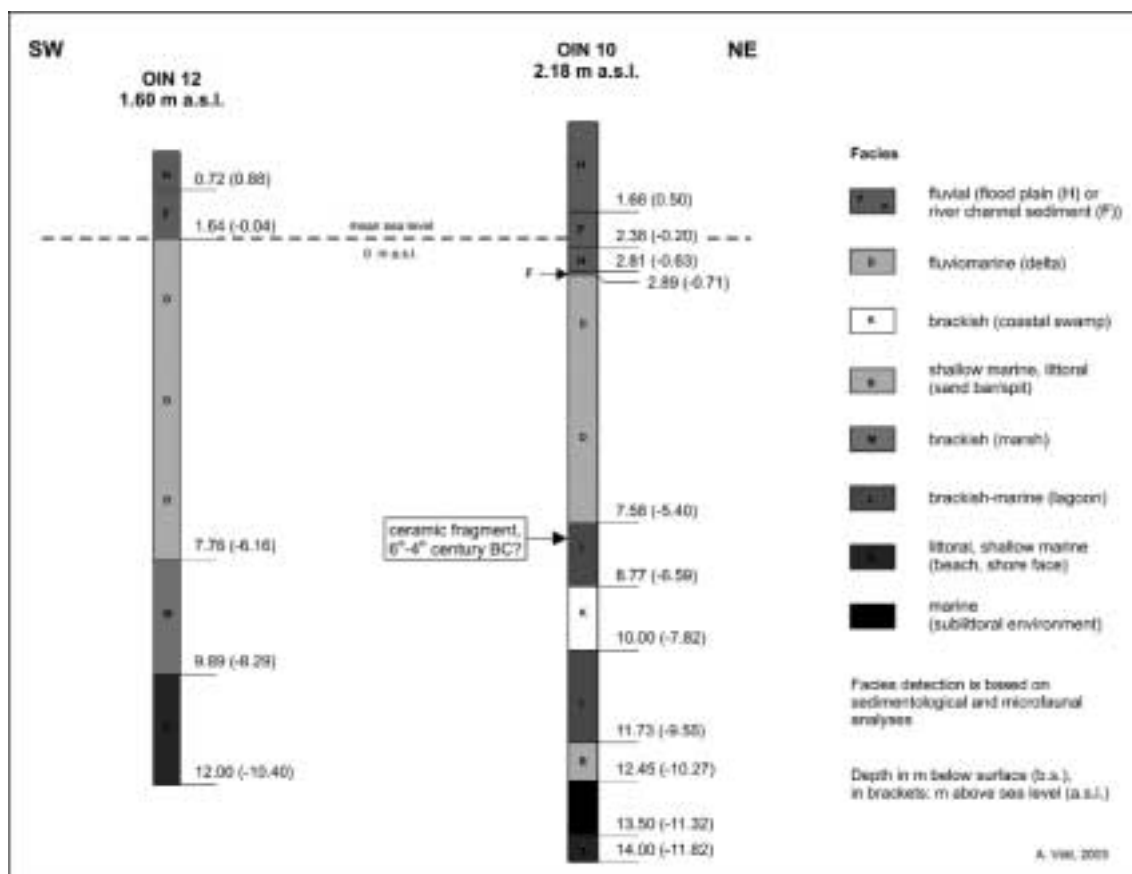

Fig. 4. Summary view of facies profiles for vibracores OIN 10 and OIN 12.

Comparing the bases of delta sediments at OIN 10 (5.40 m b.s.l.) and OIN 12 (6.16 m b.s.l.), there is a weak sedimentation gradient to the southwest. This corresponds with the main flow direction of the modern Acheloos river. The profiles show that there still was deltaic sand sedimentation at OIN 12 when subaerial flood channel sediments prevailed at OIN 10.

CHRONOLOGICAL RECONSTRUCTION OF HOLOCENE LANDSCAPE CHANGES FROM RADIOCARBON DATES

Until now very few radiocarbon dates from the Acheloos alluvial plain have been published. Selected samples from the above mentioned sediment core profiles have been submitted for AMS ^{14}C age analysis. Here we present radiocarbon dates for sediment core OIN 1 which is situated approx. 4.6 km northeast of OIN 4 and approx. 1 km north of the former island of Monasteria Panaghias (see Fig. 2). Fig. 5 shows the simplified facies stratigraphy. The profile is characterized by a clear regressive sequence. Sediments of a marine environment are succeeded by brackish-lagoonal deposits, the latter being covered by peat layers and limnic sediments. Three independent phases of marine incursion occur from 12 m below surface up to the modern land surface. Three peat layers represent three phases of comparatively quiet sedimentary conditions (4.92 - 4.82 m b.s.l., 2.38 m b.s.l., 1.66 - 0.43 m b.s.l.).
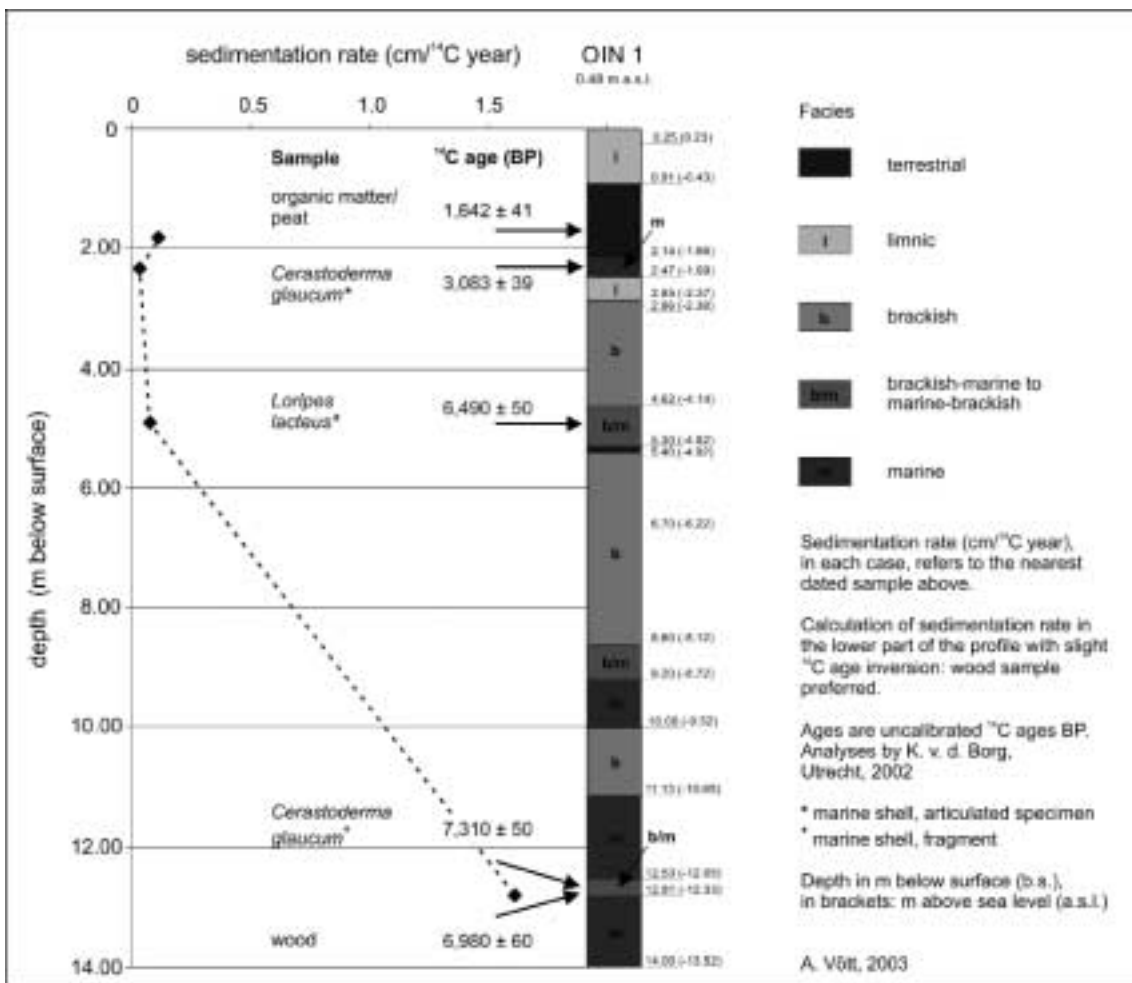

Fig. 5. Facies profile, ^{14}C dates and sedimentation rates for OIN 1.

Chronologically, we were able to discern four different changes in sedimentary conditions. Between 12.33 and 12.05 m b.s.l. there is a phase of freshwater input in a marine environment leading to a relative sweetening. A wood fragment (OIN 1/29 H) from this level yielded an AMS ^{14}C age (all ^{14}C ages are conventional ages, i.e. uncalibrated ages) of $6,980 \pm 60$ BP. A single valve of *Cerastoderma glaucum* (OIN 1/28) which was found at an inconsiderably higher position gave $7,310 \pm 50$ BP as a ^{14}C age. In spite of the risk of a large "old wood effect" we prefer the first sample to break up the slight age inversion. As to OIN 4 and OIN 5 there are no sedimentological features corresponding to this first dated event at OIN 1.

The marine incursion present at OIN 1 at 4.82 - 4.14 m b.s.l. shows a ^{14}C age of 6,490 ± 50 BP (single valve of *Loripes lacteus*, OIN 1/12). This incursion corresponds to the one we found at OIN 5 from 4.33 - 3.38 m b.s.l.; at OIN 4 it seems to be identical to the marine incursion at 3.75 m b.s.l. which we were able to detect geochemically. A complete specimen of *Cerastoderma glaucum* (OIN 1/7) yielded 3,083 ± 39 BP for the youngest marine incursion. This corresponds to a calibrated age of 1404 - 1310 cal B.C. (already corrected for marine reservoir effects). Again, the neighbouring cores show corresponding events: OIN 5 at 2.70 - 2.12 m b.s.l. and OIN 4 at 3.06 - 2.71 m b.s.l.. According to their depth, the marine sediments we found at OIN 9 (3.62 - 2.97 m b.s.l.) should have been deposited during the same marine incursion at about 3,000 B.P. Taking into account the ceramic fragment at OIN 10 at 5.72 m b.s.l. within lagoonal sediments, and its preliminary archaeological dating to the 6th to 4th century B.C., we hypothesize that these sediments correspond to the lagoonal phase following the youngest marine incursion at OIN 9.

We know from ancient sources that during the time of continuous occupation of Oiniadai (5th to 2nd century B.C.) its shipsheds were actively used and of great strategic importance. Our study shows that at this time a narrow embayment which entered the Lesini area from western direction and which had its central axis south of OIN 5 and OIN 4 must have existed. This embayment was of primarily lagoonal nature. We detected at least two cases when sudden marine incursions affected the water bodies. Originally, the bay must have extended to the E far beyond OIN 10 where the lagoon had its deepest parts. Later, this lagoon was abruptly cut off by abundant delta-ic sedimentation. The Acheloos delta which passed northeast of Oiniadai initiated the final silta-tion processes affecting the Lesini area. The former lagoon of Oiniadai became increasingly narrower, and was concentrated towards the southern part of the lowland around OIN 9, mainly supplied by karstic springs from Trikardo and Kounovina (see above). Our results match well with a course interpretation of the architectural remains of Oiniadai's shipsheds. We estimate that the slipways could only be used properly when sea level was at -1.70 m below present terrain sur-face which corresponds to approx. 1.20 m below present sea level. Furthermore, we assume that the ancient ships required a minimal water depth of 0.75 m and a maximum water depth of 2.00m. Consequently, the corresponding sedimentary surface lies between 1.95 m and 3.20 m b.s.l. (compare sediment core profile OIN 9 in Fig. 3) for the time when the slipways were oper-ated.

Following the marine incursion at OIN 1 another change in environmental conditions took place. A peat sample from the youngest phase of quiet sedimentation yielded an age of 1,642 ± 41 BP. In the more central parts of the study area no corresponding features could be found.

Regarding the sedimentation rates calculated for OIN 1, there must have been an extremely strong sedimentation rate until approx. 6,500 BP (see Fig. 5). The reasons are still unclear. After 6,500 B.P. sedimentation rates clearly decrease and show that the landscape became much more stable and appropriate for settlement activities.

Fig. 6 summarizes the results of AMS 14C dates from the Acheloos alluvial plain and the coastal plain of Palairos. The ^{14}C age – depth relations for the outermost southeastern and outer-most northwestern parts of coastal Akarnania do not correspond to a curve for the eustatic sea level rise. Uncalibrated ^{14}C ages are compared with sampling depth below terrain surface; results from non-littoral samples were not related to actual water depths. Further, the dates shown in Fig. 6 refer to different materials from different sedimentary environments (see table within Fig. 6). Nevertheless, this relation can give important information about irregularities and/or trends of the sedimentary evolution which is, of course, controlled by sea level.

The sampling points in Fig. 6 do not show any systematic discrepancies in depth for samples of similar age. Both areas seem to be characterized by comparable vertical crustal movements. Possibly, the ^{14}C age yielded by OIN 1/12 is a little bit too old due to reworking processes affect-ing the shell. The phase of strong sedimentation ends between 6,000 BP and 5,000 BP. It is doubt-ful that relative sea level in the region has ever had a higher position than today (see also Fouache, this volume) For southern Greece, Kelletat (2002) reported a sea level maximum at 5,200 BP, a subsequent decrease until 3,500 BP and, finally, a gradual rise until the modern day. But for the highly tectonically active Akarnania, things may be different and modern sea level may be the
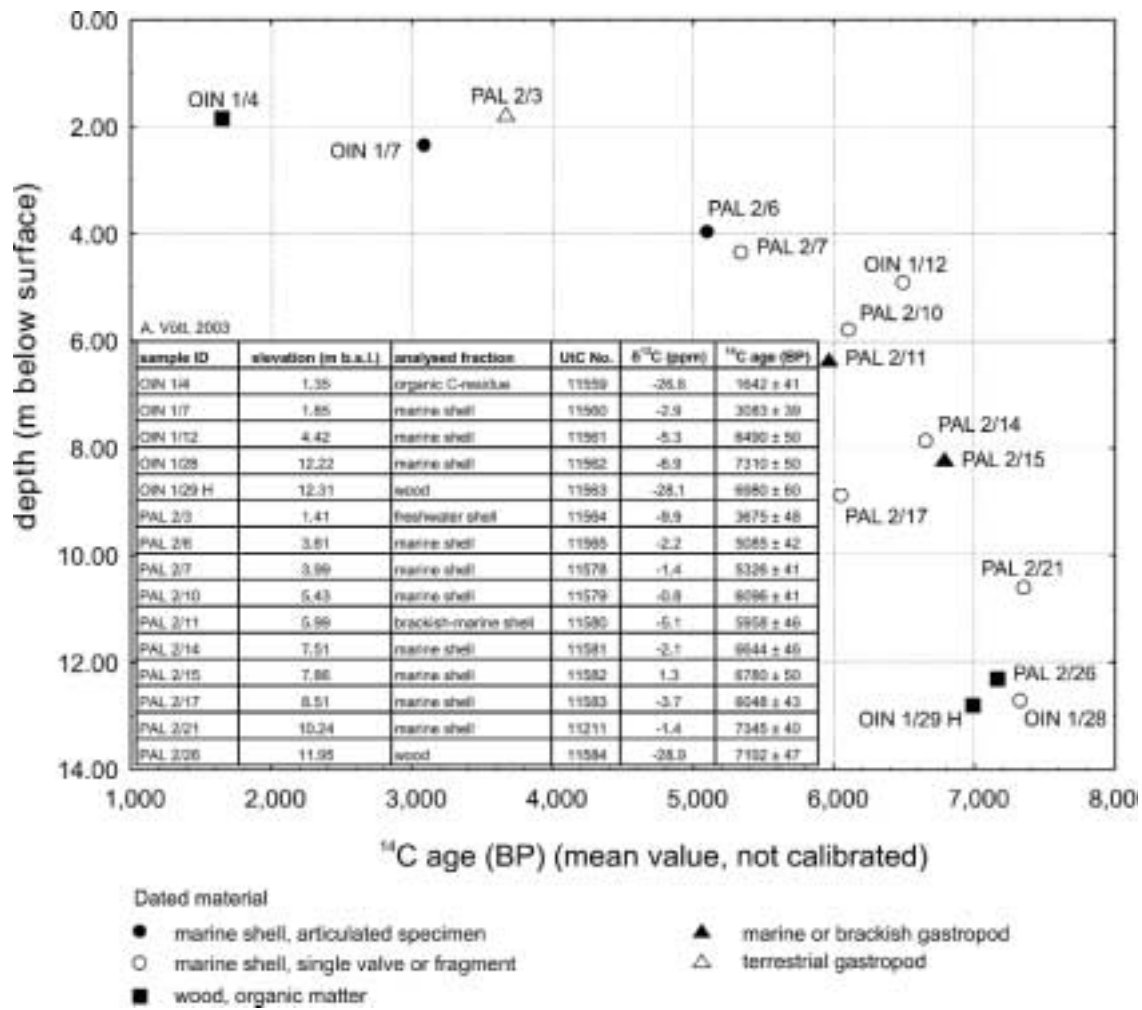
The embedded data table within the figure reads:

sample ID	elevation (m b.s.l.)	analysed fraction	UtC No.	δ13C (ppm)	14C age (BP)
OIN 1/4	1.35	organic C-residue	11559	-26.8	1642 ± 41
OIN 1/7	1.85	marine shell	11560	-2.9	3083 ± 39
OIN 1/12	4.42	marine shell	11561	-5.3	6490 ± 50
OIN 1/28	12.22	marine shell	11562	-6.9	7310 ± 50
OIN 1/29 H	12.31	wood	11563	-28.1	6980 ± 60
PAL 2/3	1.41	freshwater shell	11564	-8.9	3675 ± 48
PAL 2/6	3.61	marine shell	11565	-2.2	5085 ± 42
PAL 2/7	3.99	marine shell	11578	-1.4	5326 ± 41
PAL 2/10	5.43	marine shell	11579	-0.8	6096 ± 41
PAL 2/11	5.99	brackish-marine shell	11580	-5.1	5958 ± 46
PAL 2/14	7.51	marine shell	11581	-2.1	6644 ± 46
PAL 2/15	7.86	marine shell	11582	1.3	6780 ± 50
PAL 2/17	8.51	marine shell	11583	-3.7	6048 ± 43
PAL 2/21	10.24	marine shell	11211	-1.4	7345 ± 40
PAL 2/26	11.95	wood	11584	-28.0	7192 ± 47

Fig. 6. ^{14}C age – depth relations for samples from the Acheloos alluvial plain and the coastal plain of Palairos (modified from Vött *et al.*, 2003b).

highest ever experienced. One possible reason for this could be the subduction of the Adriatic beneath the Aegean microplate not far from Akarnania; it is connected to a clear subsidence of coastal land masses. Future studies should aim for several objectives: (1) to produce more 14C dates from coastal areas in order to separate local from regional tectonic influences, (2) to eliminate or minimize disturbing factors in order to isolate purely eustatic sea level changes, and (3) to document more or less catastrophic or gradual geomorphological events and their effects on ancient human settlements.

SUMMARY

This paper presents selected results from geomorphological-palaeogeographical studies of landscape changes in the area of the Acheloos river delta (northwestern Greece) during the Holocene. Vibracores were used to obtain detailed stratigraphic information about Holocene coastal sediments. Geochemical and microfaunal assemblage analyses gave further information about sedimentological processes. Reconstructions of landscape changes were based on horizontal and vertical changes in sedimentary facies. During the last two field campaigns 29 cores were obtained; here, the results of 6 cores are presented in the context of case studies.

Stratigraphic profiles in the area of the former swamps of Lesini document a regressive cycle. Deposits from a fully marine environment are succeeded by a shallow marine facies, and subsequently by sediments of a lagoonal and/or marshy environment. Siltation of the former marine bay is related to the formation of sand bars or sand spits resulting from longshore sand transport. These barriers sealed off the bay between Kalubitsa and Kounovina preventing open marine con-

ditions. We stress the following results: (i) The siltation process is not directly caused by delta channel sediments of the Acheloos; most of the sediments piled up in the Lesini area can be traced back to the sea. (ii) In a later phase a long-lived, narrow lagoonal bay ran from west to east at the southern margin of the Lesini lowland. It possibly corresponds to the former prolongation of the modern bay north of Kounovina. (iii) Sediments representing marine incursions were found in the upper parts of the studied profiles. According to 14C analyses of an adjacent profile the younger incursion dates back to the second half of the second millennium B.C.. In the eastern part of the area this incursion is followed by the presence of a lagoon. It is probably this lagoon which guaranteed a connection between the shipsheds of Oiniadai and the sea. (iv) Sediments of the Acheloos delta sensu stricto are concentrated in the area of the modern river channel.

According to ^{14}C dating results, there was a very high sedimentation rate until 5,000 – 6,000 ^{14}C years BP. slower landscape evolution during the following phase seems to have been more favorable for the colonisation of the area.

Neotectonic impact on relative sea-level fluctuations over the past 6,000 years: examples from Croatia, Greece and southern Turkey

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INTRODUCTION

Sea level rose for glacial eustatic reasons up to about 5000 BP. If we are to go by the geo-physical loading models proposed by Nakada and Lambeck (1988) and Peltier (1998) the global sea level may have continued to rise.

Field data from the Adriatic, the Aegean and the Eastern Mediterranean seas give evidence of sea levels different from the present one over the past 6,000 years (Blackman, 1973; Fleming, 1979; Fouache 2001). Our areas of study are located in the northern Adriatic Sea, the Cyclades, and southern Turkey (Fig. 1). One of the ways to discuss the validity of models (Fouache and Dalongeville, in press) is to compare field evidence with sea-level predictions provided by global isostatic models (Fig. 2) (Lambeck, 1995; Lambeck and Johnston, 1995; Peltier, 1998).

GEOLOGICAL SETTING

The interest of these three zones is that they are located in a continuum constituted by the Dinaro, Helleno, Tauric arc (Fig. 3). Along this continuum where, except in the Cyclades, lime-stone is dominant, we observe a great variability in geodynamic and tectonic contexts, as shown on a localisation map of recent earthquakes (Fig. 4). At the same time bio-climatic and hydro-climatic conditions vary considerably from north to south, especially in seawater temperature, resulting in a non homogenous distribution of bio-indicators of sea level such as vermetids.

METHODOLOGY

Recent research has focused on bio-indicators such as vermetids and sectors of tectonic uplift easier to study, with radiocarbon dating (Pirazzoli *et al.*, 1996). Unfortunately in the sectors cho-sen, the relative submersion of shorelines is a dominant dynamic. In order to reconstitute the rel-ative sea-level changes in those areas, because of the geological and geodynamic context it is necessary to compare and contrast the information provided by the different markers and sea-level indicators from one area to the other. Following a classic method (Fleming, 1979), we have carried out a series of divings and seashore surveys, looking for geomorphological (notches and beach-rock) and archaeological indicators of ancient sea levels. In the case of the islands of
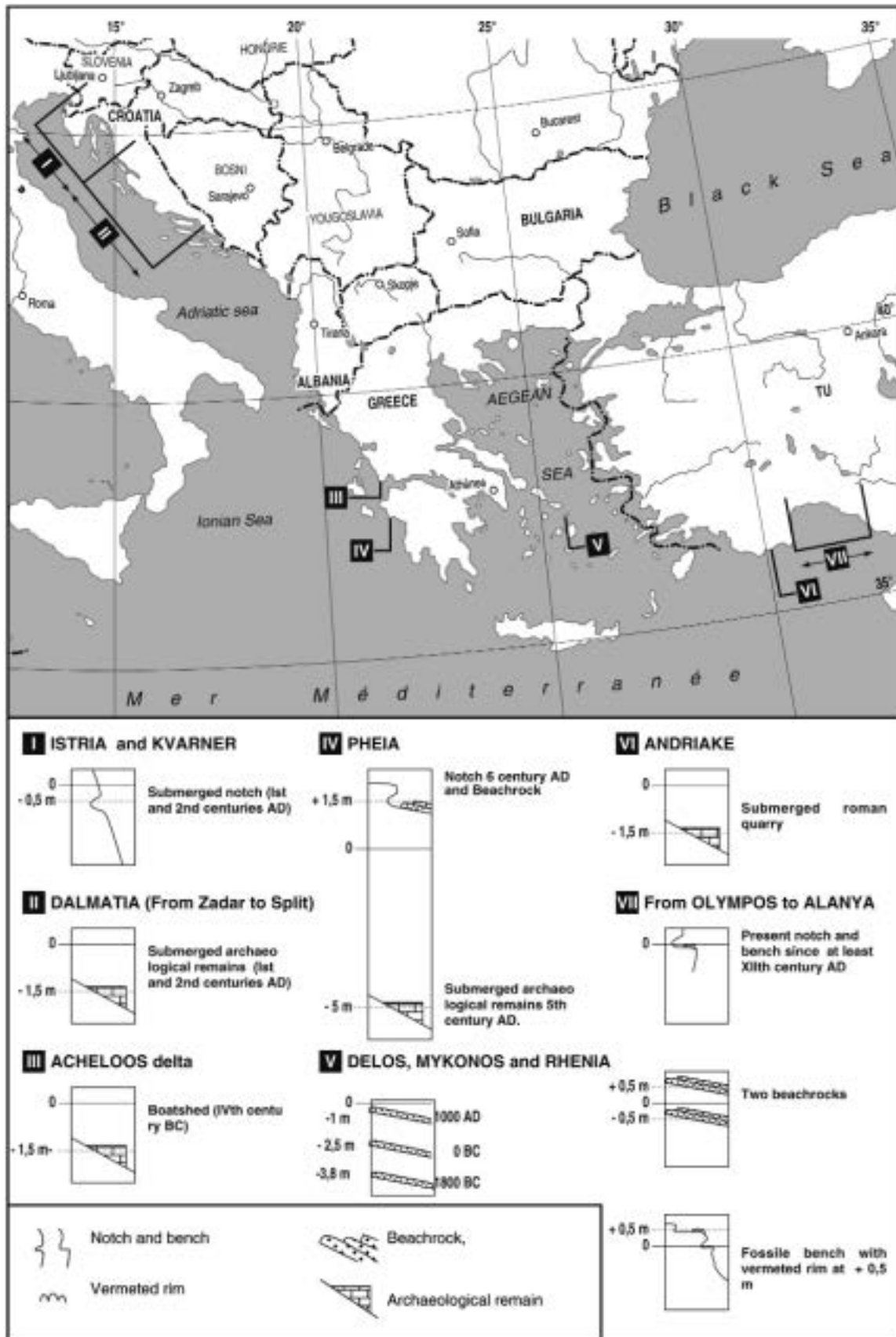
Fig. 1. Relative sea-level fluctuations and sea-level indicators in Adriatic Sea and Eastern Mediterranean Sea.
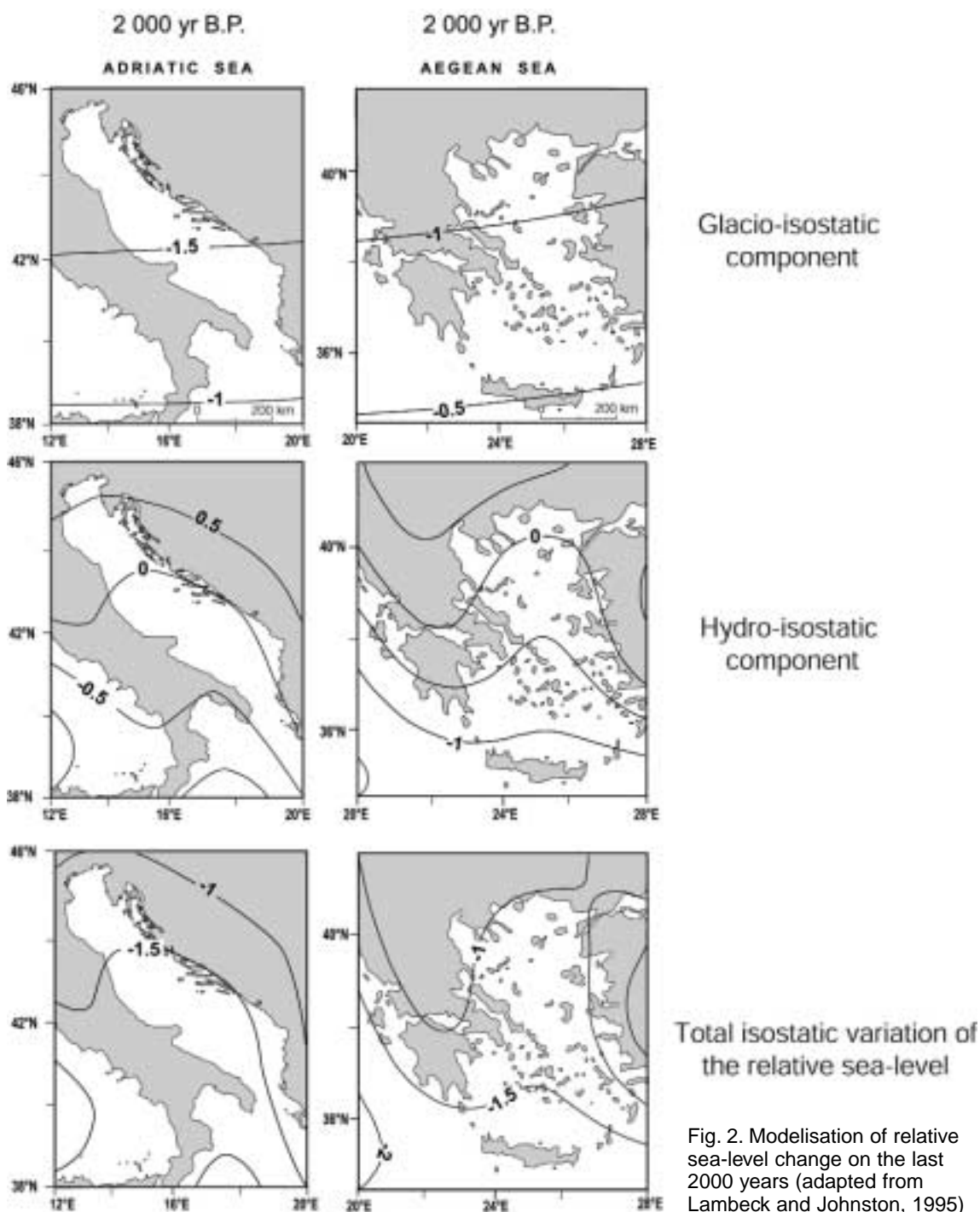
Fig. 2. Modelisation of relative sea-level change on the last 2000 years (adapted from Lambeck and Johnston, 1995)

Mykonos, Rhenia and Delos (program in progress with the French School of Archaeology in Athens), we have prolonged our research by radiocarbon datings carried out on beachrock cement. Beachrock is formed in the intertidal zone by carbonate cementation inside the beach during the stabilization of the shoreline and is only made visible during the retreat of the coast-line (Dalongeville and Sanlaville, 1984; Dalongeville, 1986). Due to the short time required for its formation, beachrock can be used as an indicator defining ancient coastlines as well as ancient sea levels. The main problem is dating its origin using ^{14}C. The most reliable method comprises the manual extraction of the cement and the sorting of each sample according to the chemistry and morphology of the cement (Bernier and Dalongeville, 1988), but this method cannot be used for little developed cement. In our case cements were studied using microscope polarizing,
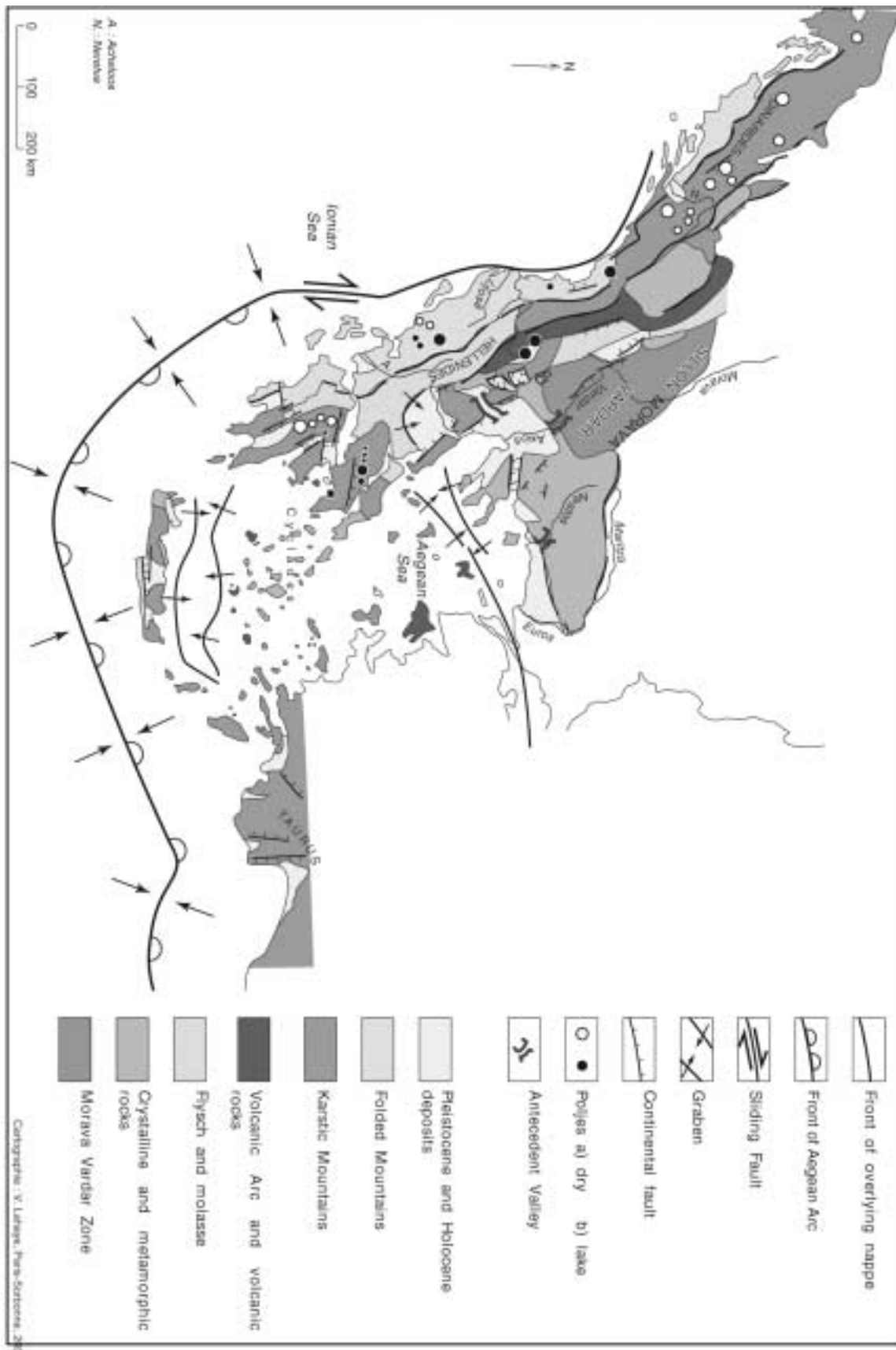
Fig. 3. Morphostructural map of the area (adapted from Dufaure, 1993).
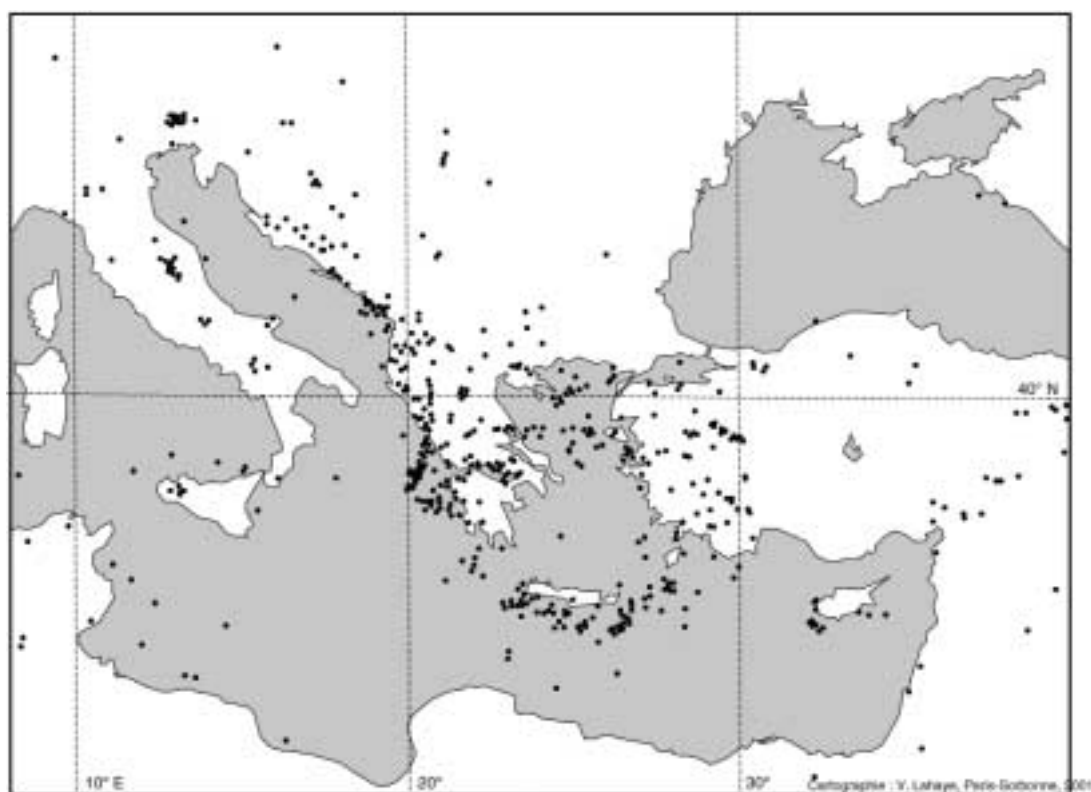
Fig. 4. Earthquakes between 1964 and 1997 (above 5 on Richter scale) (CNRS, JPGP).

cathodoluminescence and MEB. This study allowed us to ensure that the carbonate elements and structures that constitute the samples are, at least partly, incorporated in the intertidal zone. It also led us to choose ^{14}C AMS method datings on the full sample: diagenetic cements seemed difficult to extract manually and the sources of carbonate pollution are limited in the crystalline context of Mykonos-Delos-Rhenia.

RESULTS

A submerged notch corresponding to a sea-level lower by about 50 cm than present, can be observed in several places along the Croatian coast, between Poreç and Zadar (Fouache *et al.*, 2002). A number of submerged archaeological remains like Roman quarries, fish-ponds, jetties, give evidence that the notch corresponds to the sea-level in Roman antiquity, 2000 years ago. South of this area, from Zadar to Split, Roman submerged archaeological remains are related to a sea level lower by about 1.50 m than present (Fouache, 2001).

Ancient Pheia (Fouache and Dalongeville, 1998), which is now completely under water, situated in the Bay of Aghios Andreas, on the northern side of the cape of Katakolon in Ilia, was the port of Olympia during Greek and Roman times. It is a good example of the high tectonic activity at the front of the Aegean Arc. At the bottom of the bay a fossil beachrock and a fossil notch can be observed (Fig. 5). At the end of the 5th century AD, a 6.5 m tectonic subsiding movement drowned the site of Pheia, thus providing the sea with an enormous amount of sediments which it shaped into a prograding beach including extremely varied elements, some taken from the submerged city (ceramic, slags, stones), some from the cliff. Later, at an undetermined period, the whole lot was raised, thus leaving the archaeological vestiges 5 meters deep under water and raising the top of the intertidal zone of the beach up to 1.5 m

In Mykonos, Delos and Rhenia, located in the center of the Cyclades, in a geological context of back arc basin, two or three submerged beachrock benches separated by sandy areas can be observed (Desruelles *et al.*, in press). These benches correspond to two or three beachrock generations formed during stabilization phases of the relative sea level during the Holocene.
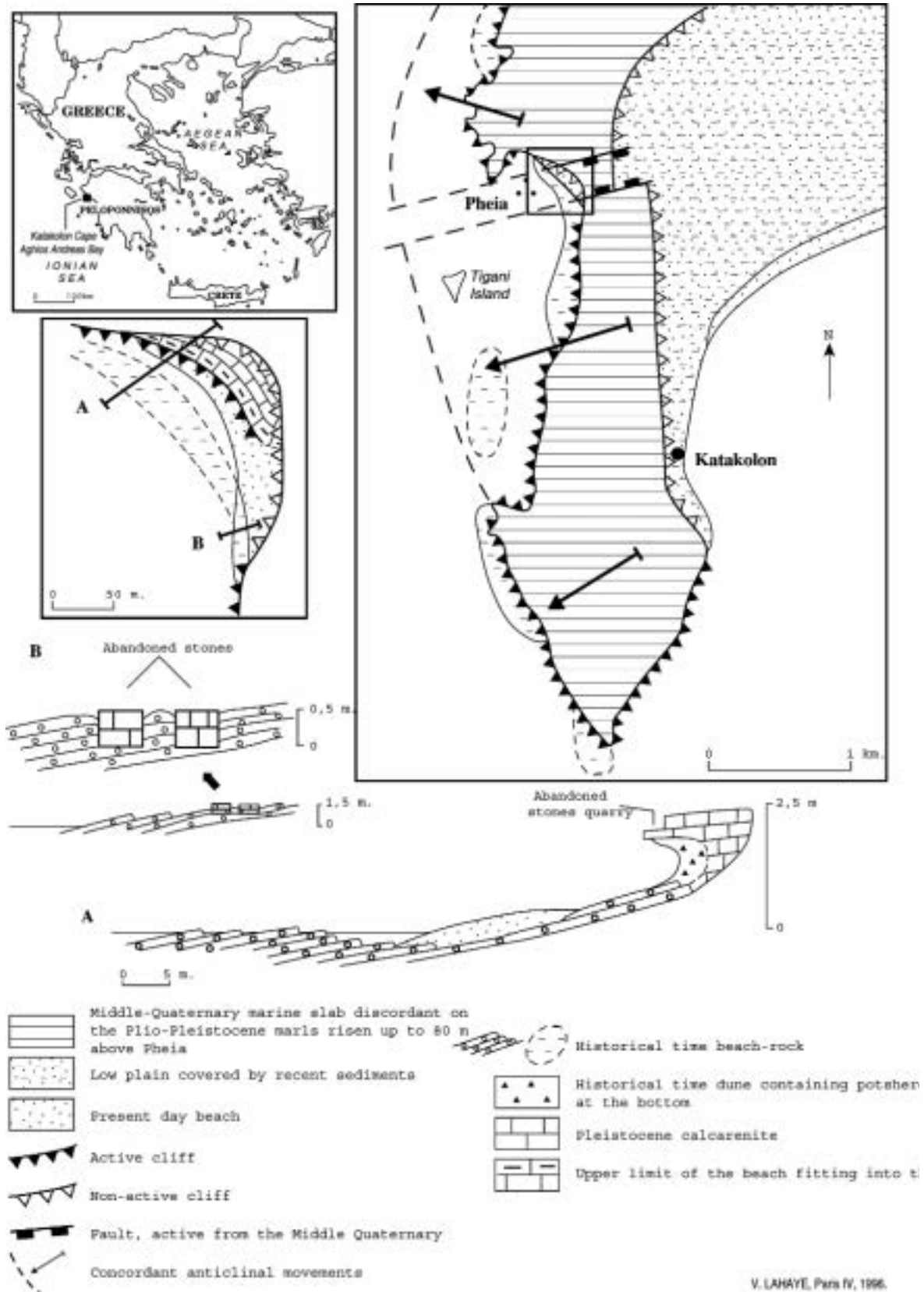
Fig. 5. Site of Pheia : geomorphological sketch.

Radiocarbon datings carried out with the AMS method on the cement (Neumeier *et al.*, 2000) of these beachrocks lead us to believe that around 1800 BC the sea level was situated 3.8 m below the present one, at -2.5 m 2,000 years ago and around -1m in 1,000 A.D. These results are consistant with the archaeological submersion observed in Rhenia and Delos and with Flemming's observations in the Aegean Sea (1969).

In southern Turkey (Fouache *et al.*, 1999), between Andriake and Alanya (Fig. 6), we can distinguish two different zones. East of the Finike peninsula, we observe two fossil shorelines (beachrock) corresponding to a sea level located 0.5 m above and below the actual one. The shoreline at -0.5 m was stable from the 4th century BC to the 4th century A.D. The present sea level characterized by a very deep notch has been in place since at least the 13th century A.D., as confirmed by the presence of archaeological remains from the Seldjoukid era. West of the Finike Peninsula, we lose track of the present notch and a submerged quarry in the Roman site of Andriake indicates a submersion of 1.5 m. We interpret the dissymmetry on either side of the Finike peninsula as a sign of seismic activity during the Byzantine era that might correspond to the Early Byzantine Paroxysm (Pirazzoli; 1986)

DISCUSSION

In all three zones of study we observe a difference between field data and Lambeck's model (Fig. 2). These differences are due to the neotectonic factor, which seems essential to explain
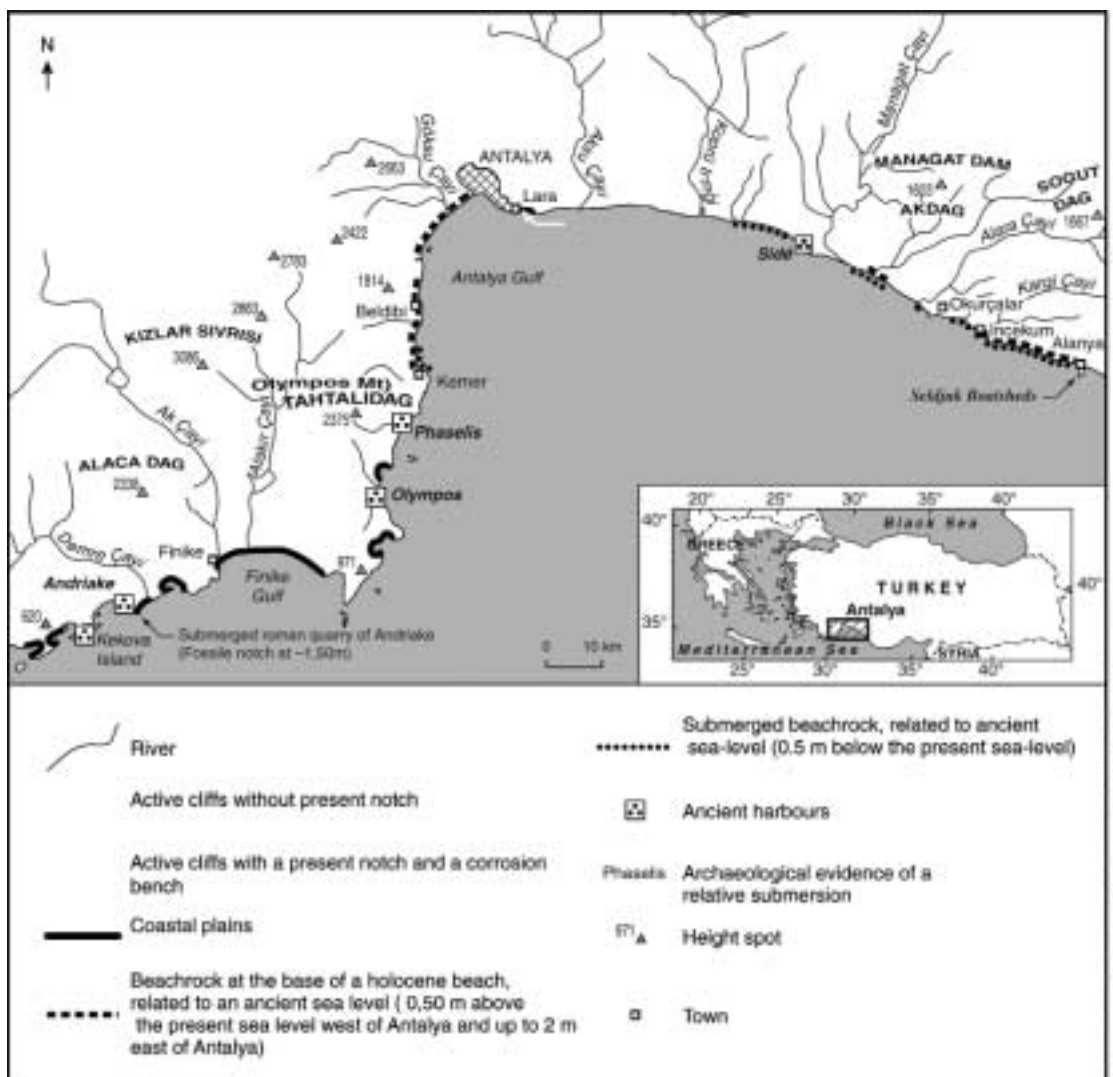

Fig. 6. Holocene fossile sea-level indicators between Andriake and Alanya.

Late Holocene relative sea level fluctuation in this part of the Mediterranean Sea. The north of the Adriatic Sea belongs to a low tectonic activity zone. The notch observed at 50 cm below the actual mean sea level gives testimony of a long period of sea level stability, with the first and second centuries A.D. in the middle. The fact that, south of Zadar, the seashore line from the same period is located 1.5 m below the actual mean sea level is undoubtedly due to post-Roman tectonic subsidence.

Whereas on the front of the Aegean Arc local and regional tectonic movements are dominant, in the back arc basin of the Cyclades there is a continuous submersion, related to the hydro-isostatic component amplified by a slow subsidence on a large scale.

Southern Turkey is in an intermediate position. The west of the Finike peninsula is related to the Aegean Arc system where a strong tectonic is dominant. To the east of the Finike peninsula as far as Alanya and even the Syrian border, we observe at least two fossil shorelines on either side of the present shoreline.

CONCLUSION

The three zones of study we have chosen to compare are located to the extremity and back of a high seismic active zone related to the Aegean Arc and its extensions. The sea level indicators and time-markers vary according to the different zones because of three factors:

- historical factors for the distribution of archaeological remains.
- bioclimatic factors for the distribution of beach-rock, notches and vermetid rims.
- geodynamical factors for the importance of neotectonics (uplift or subsidence).

Neotectonics proves to be a key-factor in the relative evolution of the sea level during the Late Holocene.

Holocene coastal evolution of western Anatolia – the interplay between natural factors and human impact

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Since the Last Glacial Maximum ca. 20,000 years ago, the Mediterranean coasts have undergone substantial changes in their geographical and geomorphological setting. The transgression of the Mediterranean Sea from ca. –120 m to its present level around six millennia ago, created marine embayments. Many of them have silted up in the meantime, partly or in the whole, because of strong delta progradation. This process was often considerably sped up due to human impact on the environment in the adjacent hinterland. As one major result, former harbour cities lost their connection to the open sea.

As for the Aegean coast of Turkey, the strongest coastline changes during the Holocene occurred in delta regions, particularly in those of Karamenderes (Scamandros), Gediz (Hermos), Kücük Menderes (Kaystros), Büyük Menderes (Maiandros) and Dalyan (Kalbis). A paper summarizing the geoarchaeological research in these areas and its link with historical sources was published by Brückner (1997). The present paper focuses on the evolution of the Büyük Menderes delta and its effects on the former harbour cities Myous, Priene and Miletos, thereby looking upon the interplay between natural factors (such as tectonic activity, sea-level fluctuations, climatic and hydrologic changes) and human impact (such as deforestation and animal husbandry).

In this context, the following topics are of special interest:
• Are there indicators for a neotectonic uplift or subsidence?
• What is the shape of the sea-level fluctuation curve for the Holocene, especially the position of sea level around 6-5 ka BP?
• When and to what extent did the human factor dominate natural changes?
• Is there a synchronic or a diachronic evolution of the Aegean coastal areas of Turkey?
• Are there indicators for catastrophic events, like tsunami and volcanic deposits?
• How does sedimentological and geological evidence match the human records?

1 - INDICATORS FOR NEOTECTONIC AND VOLCANIC ACTIVITIES

As for the general tectonic setting, it is widely accepted that the collision between the African/Arabian plates and the Eurasian plate is the reason for the westward displacement of the Anatolian microplate (see also Altunel, this volume). The strong seismic activity of the North Anatolian Fault (NAF) as well as many historic reports of earthquakes are impressive witnesses

of this ongoing drift. One result is the graben/horst structures in Western Anatolia. The grabens are the guidelines for the lower courses of the major rivers.

The subduction of the Anatolian Plate below the Aegean Plate can be proven by geomorphological criteria: in the whole of the Mediterranean, the last interglacial marine terrace (MIS 5.5) is an excellent indicator for neotectonic movements since its glacio-eustatically 'normal' position is around 4-6 m above the present sea level. So far, a MIS 5.5 site has not yet been reported from the west coast of Anatolia. This is a strong argument for tectonic subsidence during the Late Quaternary. The only exception might be Kömür Adasi in the Gulf of Akbük with lithophagae borings on a Middle Helladic wall, up to 75 cm above present mean sea level. This find is, however, very questionable.

As for tephrochronology, which may render a good event stratigraphy, the only volcanic ash layer that has been found in the west coast region of Turkey to date is that of the Thera (Santorini) eruption in 1642 B.C. It occurs in a former lake east of Izmir and in Lake Köycegiz near Kaunos; it was also unearthed during the excavation of the Minoan-Mycenaean Miletos (see also Nomikou, this volume).

2 - OUTLINES OF THE GEOARCHAEOLOGICAL APPROACH

The major purpose of geoarchaeological research in delta- and floodplain areas is to trace the maximum extension of the Holocene transgression ca. 5,000-6,000 years ago, and to decipher the shifts in the shoreline during the following regression caused by delta progradation. The main tool is percussion corings with a Cobra drilling device, reaching average depths of 10-20 m. The general stratigraphy of the strata is like this: On top of the abraded bedrock lies the transgression deposit (often pebbles in sandy matrix), indicating the 1st transition of the shoreline during the course of the Holocene sea-level rise. The littoral facies then grades into a marine one. Depending on the sedimentation rate, this stratum may be several metres thick. The 2nd transition of the shoreline occurs during the following regression. It is indicated either by another littoral facies (e.g. beach sand) or by a lagoonal layer (mostly silt and clay). The latter is evidence of the fact that meanwhile a sand bar or barrier beach developed seaward of the cored site. The lagoonal facies may change into that of a freshwater lake. The uppermost sedimentary units are deposits of the delta top and the river floodplain (river gravel, sand or fine grained alluvium).

For establishing a chronostratigraphy, the most suitable material in the drill cores are macrofloral remains (e.g. grape seed, olive stone, peat), articulated mollusc shells (although the reservoir effect is a pending problem) and, of course, characteristic, datable ceramic fragments. The different environments of deposition (marine, littoral, lagoonal, lacustrine, fluvial) have to be detected by microfauna analysis (e.g. ostracods; Handl *et al.*, 1999) or by geochemical parameters (Vött *et al.*, this volume). Given a high number of corings and datings, the data set may be used to map the position of the shoreline during different times. The reconstruction of the former sea-level fluctuations is tricky since there are seldom good indicators in the sediment cores. The best are: (a) the transgression facies at the base of the core; (b) the change from marine to littoral facies in the upper part of the core, which may be detected by sedimentological and faunal criteria; (c) coastal peat. This information must then be supplemented by archaeological criteria, like drowned ruins.

In order to decipher the impacts of natural as well as human factors, the above mentioned data must render a chronostratigraphy with high resolution, clear results from pollen analysis must be available, and the archaeological and historical information must be included.

3- CASE STUDY: PROGRADATION OF THE MAEANDER DELTA

In the following, the link between the archaeologic, prehistoric and historic sciences on the one side and geoarchaeology/palaeogeography on the other shall be demonstrated by the example of the Maeander (in antiquity: Maiandros; modern name: Büyük Menderes). The data set is also suitable for the extraction of information about the changes of the natural factors throughout the past millennia and for the evaluation of the human impact.

3.1. Literary evidence

During the peak of the Holocene transgression, the Büyük Menderes graben was partly filled with a marine embayment, the later so-called "Latmian Gulf". Meanwhile, the environment has

completely changed and the harbours of the ancient cities Myous, Priene and Miletos have totally silted up (cf. Bay, 1999; Brückner, 1996, 2003; Brückner *et al.*, 2002). The following synopsis of the literary evidence is based on Brückner (2003: 122 ff.).

Conclusions for the historical progradation of the Maeander delta in space and time may be drawn from ancient writers like Herodotus (484-425 B.C.), Strabo (ca. 63 B.C.- ca. A.D. 24) and Pausanias (ca. A.D. 110 - after A.D. 180) as well as from historical documents found in monasteries and from travellers' reports. These sources do not, however, allow an unambiguous scenario.

Schröder (1998: 94) suggests that the city later known as "Magnesia on the Maeander" may originally have been a harbour city when it was founded in the course of the Ionian colonisation and that the delta front reached the city around 800 B.C. Herodotus (5.36 and 6.8) mentions Myous, Priene and Miletos as harbour cities. (Note that Herodotus refers to the Archaic Priene) In the 7th century B.C., the delta front ran northeast of Hybanda (modern name: Özbasi), then probably still an island, since gneiss blocks from a quarry in the area north of Myous were transported to Miletos by ship for the erection of the Archaic city wall (cf. Schröder and Bay, 1996: 66). From Herodotus (5.36) we may conclude that Myous still had an open harbour around 500 B.C. According to Grund (1906), the northern branch of the Maeander river was then more active so that the northern part of the Latmian Gulf silted up more rapidly during that time. When Alexander the Great freed the region from the Persians in 334 B.C., the harbour of Myous was of some strategic importance (Brinkmann *et al.*, 1991: 9). An Early Hellenistic inscription testifies to a still well accessible harbour in Myous. Schröder (1998: 96) assumes that the city was deserted approximately 280 B.C.; according to the Eirenias inscription it was 169/150 B.C. (cf. Tuttahs, 1998: 157). There are no Roman ruins in Myous. In the 2nd century A.D., Pausanias (7.2.11) reports that the inhabitants had left the city because of unbearable swarms of mosquitos and had moved to Miletos. Pausanias (7.10.11) also describes a small marine embayment near the former city which had been cut off by the Maeander – most likely the predecessor of the present Lake Azap. In the early 1st century A.D., Myous was 30 stades (ca. 5.9 km) inland from the shoreline and the mouth of the river was between Priene and Miletos, about 50 stades (ca. 9.8 km) away from Pyrrha (Strabo 14.1.10). Around A.D. 100 the level of the pavement in the streets in the lower parts of Miletos had to be raised (Eisma, 1978: 71); this was probably due to a rise in sea level.

According to Erol (1996), the Büyük Menderes started to accumulate its delta in the centre of the Latmian Gulf; its northward shift after 500 B.C. finally resulted in the filling up of the harbour(s) of the Archaic Priene. The author assumes that when Priene was founded anew in the middle of the 4th century B.C., it was situated at a northern marine embayment, south of which the delta had already developed. When the Büyük Menderes had silted up this embayment, Priene's harbour(s) became landlocked and had to be shifted.

Philippson (1936: 10) assumes a complete silting up of the area around Miletos in the 6th century A.D. Miletos gradually lost its importance as a port city. Between A.D. 600 and 700, the former island of Lade was integrated into the delta-plain (Aksu *et al.*, 1987: 233). In A.D. 1560 a Greek sailor reported that the coast was ca. 8 km away from the city (Wiegand, 1929). The question of how he had measured this distance (along the river?) remains open.

The scenarios of the historic delta growth published so far are mostly based on evidence from literature. This is especially true for the ones of Eisma (1978) and Erinç (1978). Aksu *et al.* (1987) add evidence from sedimentology, Erol (1996) uses the interpretation of aerial photographs as a further source of information, and Schröder and Bay (1996) excerpt information from drillings for water wells, as well. It is evident that these sources leave quite some space for different interpretations. This is also true for the latest approach by Tuttahs (1998: 153 ff.). He interprets the filling up of the Latmian Gulf in three phases: (I) the Maeander delta prograded from Söke to Priene along the north-west coast at the foot of Mykale mountains; (II) it turned south from Priene to Miletos; (III) the still open parts in the east and the south of the gulf silted up from Myous to Miletos along the south-east coast. The author places the transition from phase I to phase III around 300-250 B.C. Phases II and III ran parallel ca. 300 B.C. - 0 B.C./A.D.

3.2. Geoarchaeological evidence

By geoarchaeologic means, potential Archaic to Classical Greek harbour sites were identified in the embayments west of the Myousian peninsula, i.e. between Castle hill and Settlement hill, and south of Settlement hill. In the vicinity of Myous, the transiton from marine to lacustrine facies must have occurred already in Hellenistic times. Lagoonal conditions prevailed in Hellenistic-Roman times. In the southwest, the lacustrine environment started in the 1st or 2nd century A.D. and partially prevailed until Modern times. In the east, the brackish and shallow Lake Azap is what remains of the former marine embayment.

Priene was founded anew in Late Classical time around 350 B.C. Under palaeogeographic perspective the most interesting question is that of the harbour site(s), a topic whereof the historic sources remain silent. Potential areas are the eastern and western embayments at the foot of the promontory of Priene. Ceramic and ^{14}C stratigraphies of drill cores led to the following conclusions: In the eastern embayment, marine conditions prevailed at least until the 13th/12th century B.C. Thereafter, a slight regression can be proven by a peat dating from the second half of the 2nd millennium B.C. In the mid-4th century B.C, this embayment had already turned into a freshwater lake. For that time, a potential harbour site can be ascertained in the western embayment where water depth was still several metres and a lagoonal environment existed until the beginning of the Roman Imperial era. Definitely freshwater milieu did not exist before the 3rd century A.D. This embayment was filled with sediments more slowly than its eastern counterpart since it was sheltered from alluviation by the river due to the leeward position behind the promontory of the Priene rock.

During the peak of the Holocene transgression, the area of the later city of Miletos was composed of islands. One of them hosted the earliest settlement in the area of the later Athena Temple dating from the second half of the 4th millennium B.C. When the Minoan settlers arrived around 1900 B.C. this island topography is likely to have persisted; however, hints of an already existing connection with the adjacent mainland by a sandbar (tombolo) cannot be neglected. The palaeogeographic setting changed to a peninsula during the Minoan-Mycenaean occupation phase. The sediments were mobilized by coastal longshore drift and human-induced denudation from the adjacent slopes. It is at least since the Archaic period that the Milesian peninsula extending into the Latmian Gulf is known from literary sources and archaeologic evidence (city wall). The Roman time – and especially the Roman Imperial era – witnessed strong siltation processes around Miletos. It was then that the southeastern part of the Latmian Gulf was cut off, thereby creating the "Milesian lake" out of which the still brackish Bafa Gölü developed.

Tradition has it that the Milesian peninsula had four harbours, of which only the Lions' Harbour and the Theatre Harbour have been definitely identified to date. Our research in the Lions' Harbour showed an enormous increase in siltation between the 1st century B.C. and ca. A.D. 400, when the average sedimentation rate was doubled compared to the centuries in Classical Greek and Hellenistic times. It was even 21 times higher than during the period 4th-2nd millennia B.C. The corings within the Theatre Harbour unearthed no artifacts older than the Roman Imperial era; therefore, it must have been dredged in the 1st or 2nd century A.D. when also the theatre was renovated. The geoarchaeological approach also revealed that a good natural setting for the third harbour was provided close to the earliest settlement near the later Athena Temple. Another potential harbour most likely existed to the east of the Milesian peninsula, in a leeward position to winds from the west (see below).

The data set of archaeological and ^{14}C ages from the lower alluvial plain and the delta region of the Büyük Menders is suitable for the establishment of a locally valid sea level fluctuation curve for the Holocene. It seems to have a relative peak around 6-5 ka BP, after the strong late Pleistocene – Holocene sea level rise, and a relative low around 3 ka BP. This shape of the curve is similar to Kayan's (1995) sea level curve established at Troia. However, in our case this glacio-eustatic curve is shifted downward by a factor of 0.7 m/ka due to the ongoing subsidence of the Menderes graben. In several other regions of the Mediterranean, sea level reached its highest position during the Holocene only today and was definitely lower around 5 ka BP (e.g. Silvan, this volume, for the coast of Israel; Collina-Girard, this volume, for the French coast in Provence).

3.3. Including and cross-checking geophysical data

Within the spectrum of geoarchaeological tools, the geophysical ones are a good supplement to the above described methods. Geoelectric measurements may provide information about the hardrock/softrock contact even at great depths. This may help to a better understanding of the filling of the embayments during the late Pleistocene-Holocene period. Geomagnetics and georadar render valuable information about the subsurface strata and about anthropogene structures up to depths of ca. 5 m. The interpretation of these two-dimensional images must then be verified/falsified either with corings or excavations – the latter being much more expensive and time consuming than the former and nearly impossible below the groundwater table. The following paragraph presents some examples of the integration of geophysical methods – in this case carried out by Dr. H. Stümpel, University of Kiel (Germany) – into geoarchaeological research.

On several sites of the former city of Miletos, a feature on the geomagnetic images was interpreted as a city wall at a depth of 4-5 m below present surface. This was ascertained by geologic corings and later proven by the excavation. It dates to the Archaic period. The assumption of a harbour situation near the Southern Market was based on geophysical measurements. Corings confirmed an excellent natural setting for a harbour; its use seems to have ended in the Roman Imperial era. According to geomagnetic data another harbour was presumed at the foot of Kalabak Tepe, the prominent hill in the southwestern part of the Archaic city. Our research verified a former marine embayment; however, it was always of shallow water depth. While it may have been of some use in the Archaic time, the "harbour" had silted up in the early Roman era, mostly due to colluviation from the adjacent slopes. Corings in the famous Lions' Harbour falsified the geophysically interpreted harbour jetties; these features are brick and tile debris which was most likely intentionally deposited in order to relocate the marble statues of the lions when the area had already turned into a swamp.

4 - FLORAL AND FAUNAL CHANGES

Various pollen spectra show that along the Aegean coast of Turkey the climax vegetation, i.e. the natural vegetation without human impact during the peak of the Holocene (around 5,000 years ago) was a sparse deciduous oak tree forest. This is evidenced by high values of *Quercus pubescens*-type pollen grains on the one side and a fair amount of non-arboral pollen grains on the other. Already during the middle of the 2nd millennium B.C., the degradation to a macchia-type vegetation can be proven in some places. In the Archaic epoch the potential indicators for settlements are well present while the arboreal pollen shows a definite decline. The significant increase in *Olea* and *Phillyrea* pollen may indicate human impact since these species are much more frequent in the macchia than in the natural vegetation. The high amount of *Olea* may also indicate olive groves (cf. Wille, 1995).

The vegetation changes are also mirrored by the faunal changes. Peters (in press) identified bone fragments from Minoan, Mycenaen and Archaic periods of Miletos. While game was still well present during Minoan times, it significantly decreased thereafter. The occurrence of wild boar (*Sus scrofa*) and European fallow deer (*Dama dama*) confirms the presence of sparse deciduous oak tree forests. Another indicator for that biotope is the leopard (*Panthera pardus*). One characteristic aspect of the Minoan culture was the preference of goat as compared to sheep; the settlers obviously brought with them this pastoral habit when emigrating from Crete to Miletos. The predominance of goat keeping is one major factor in the degradation of the forest ecosystem to a Macchia/Garrigue-type vegetation. In post-Minoan times, however, sheep husbandry became the mainstay of small livestock exploitation; it is well known that during the Archaic period the Milesian wool was a famous article for trading. In summary, from the Minoan time to the Archaic period, deforestation is evidenced by the decrease in big game on the one hand and the increase of small ruminants and of hare (*Lepus capensis*) – an open landscape indicator – on the other. There is archaeo-zoological evidence that fishing added considerably to the diet of the Minoan site inhabitants. Some of the identified species can only be found offshore, implying the use of vessels. Fishing and sea trading activities may therefore have contributed to the deforestation of the Milesian hinterland, too.

5- VISUALIZING THE SCENARIO OF THE LANDSCAPE EVOLUTION

One of the major goals of the paleogeographic-geoarchaeologic research linked with archaeological and (pre-) historical sciences is to develop a scenario of the landscape evolution including the human impact in space and time. This is exemplified by Fig. 1 which shows the latest synopsis of the geomorphological evolution of the Büyük Menderes delta, presented in several time slices. The palaeogeographic scenario is based on ca. 200 percussion corings and their geoarchaeologic interpretation as well as on data from archaeology and historical sciences. A future step will be the production of a video sequence including a digital 3D elevation model derived from ERS Tandem radar data and satellite images.
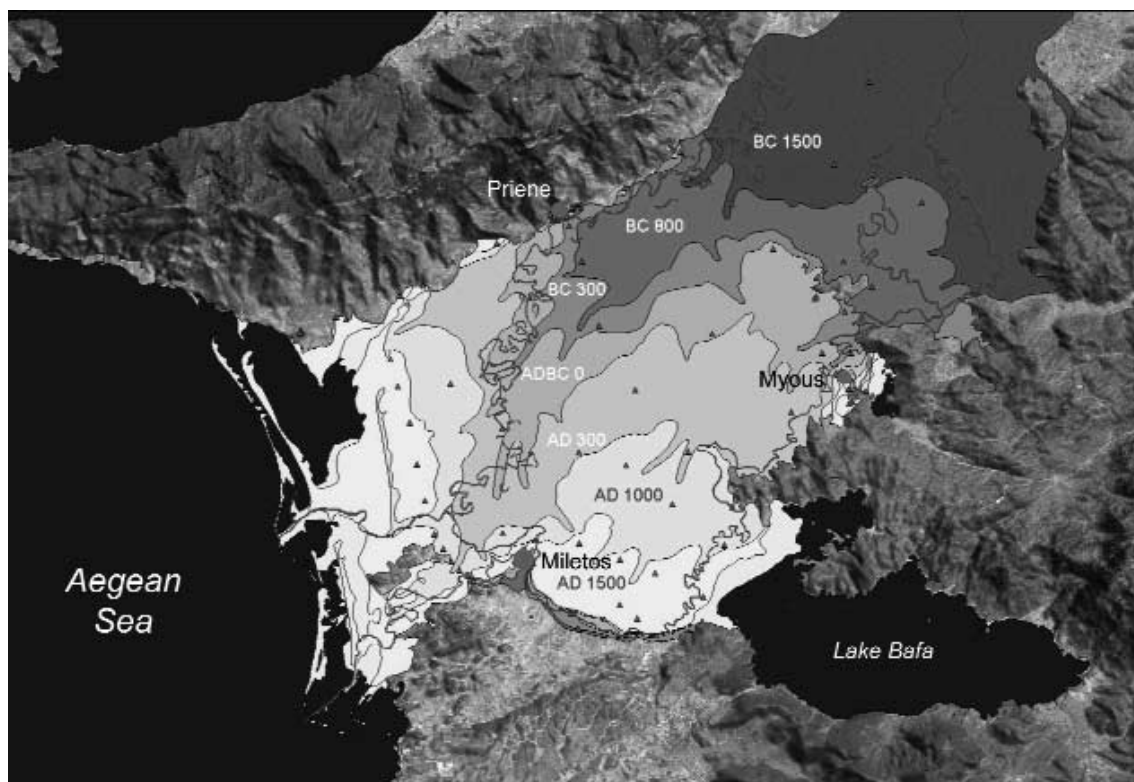
Fig. 1. Scenario for the progradation of the Büyük Menderes delta during the past millennia. During the peak of the Holocene ca. 6-5 ka BP, the marine embayment extended much further to the east covering the whole area of the floodplain visible in this figure. A given age refers to its nearest seaward coastline.

Sinking of Venice over the last three centuries: input from Canaletto's paintings and early photographs

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ABSTRACT

The sea level is expected to rise from 10 to 80 cm by 2100 as a consequence of the global warming. In addition, Venice is affected by a local subsidence, mainly of tectonic origin. In the recent past, pumping of underground water for industrial purposes has worsened this situation. Relative sea level (RSL) rise is a combination of the two above challenges and is a crucial issue for the safeguard of Venice and its historical buildings. The phenomenon over the last three centuries has been investigated by using a proxy of mean sea level: the level of the algal front on palaces. Algae, and particularly the *Laminaria*, mark the average high sea level. This indicator was accurately reported by the Venetian painters Antonio Canaletto (1697-1768) and his pupils, mainly Bernardo Bellotto (1722-1780), in their "photographic" paintings made with an optical *camera obscura* in the first half of the 18th century. These paintings extend our knowledge about Venice submersion back in time for almost three centuries, which include the ending part of the Little Ice Age and the recent warming. Nowadays, after the relative sinking, sea water wets Venice palaces for an additional 69±11 cm. High tides and flooding waters reach brick and plaster which are rapidly destroyed by salt crystallisation cycles. The rise of the algae belt, however, has also increased by some 8 cm, as a sum of two contributions: the increased height of waves generated by motor boats, and the dynamic increase of the tidal wave after the excavation of some canals. With the above corrections the bulk submersion of Venice estimated from all the analysed paintings is 61±11 cm, which corresponds to an average sinking ratio 2.3±0.4 mm yr^{-1}.

IntroductionAbstract. Relative sea level (RSL) rise is a crucial issue for the safeguard of Venice and its historical buildings. The phenomenon over the last three centuries has been investigated by using a proxy of mean sea level: the height of the algae front on palaces. This indicator was accurately drawn by Canaletto and his pupils in their "photographic" paintings made with an optical camera obscura. The positions of the fronts in the 18th Century and the present were compared. The RSL rise is due to a combination of natural and anthropogenic factors which affected the land subsidence. An analysis was performed to establish the long-term trend and distinguish between natural and anthropogenic contributions. A prudent scenario for the future would suggest a rate between 1.9±0.4 mm yr^{-1} and 2.3±0.4 mm yr^{-1}.

Venice risks being submerged as a consequence of two problems: local land subsidence and sea level rise as a consequence of thermal expansion of sea water and land ice melting (IPCC, 2001). They both contribute to what is referred as Apparent Sea Level Rise (ASLR) where the

term "apparent" indicates that even when the land is sinking the result from the point of view of the city is a sea level rise. In practice, the ASLR is the submersion rate of Venice. Regular tide-gauge monitoring was started in 1872 and shows an ASLR of about 30 cm. The storm surges are known from documentary sources since AD 787 and their frequency has exponentially increased in the last decades (Camuffo, 1993; Enzi and Camuffo, 1995; Camuffo and Sturaro, 2002, 2004). Ammerman *et al.* (1999) and Ammerman and McClennen (2000), on the grounds of archaeological evidence, better documented from AD 200 to 1400, suggested 1.3 mm yr^{-1} average ASL rise, with a lower rate in the early period and a greater one in the modern period. The dark period between archaeological and instrumental data should be investigated with other proxy data.

The Venice painter Antonio Canal, nicknamed Canaletto (1697-1768) and his pupil Bernardo Bellotto (1722-1780) made accurate reproductions of Venice buildings using a *camera obscura* on the site and they also reported the algal belt on buildings (Camuffo, 2001; Camuffo and Sturaro, 2002, 2003). In the *camera obscura* (Fig.1) the light beam penetrates through a lens, is reflected by a mirror or a prism, and is projected onto a glass surface, where a sheet of paper was placed. Then the painter drew in all the contours, obtaining a "photographic" painting. In a number of paintings, the brown-green front left by algae (mainly the *Laminaria* alga) is visible on some buildings. This front is a biological indicator of the average high-tide level (HTL) and is locally called *Commune Marino* (CM). In the past, the CM was in some cases also engraved on buildings with the initials CM, but this information was lost for the earliest times. The standard deviation of the yearly sea level fluctuations, and consequently of the CM, is 3.8 cm.
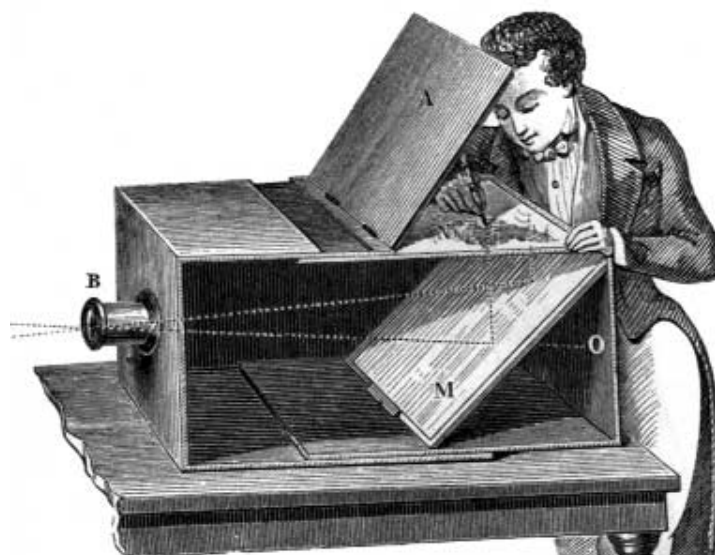

Fig. 1. Principle of operation of the *Camera obscura* in a compact box model (after Ganot, 1860).

The use of this indicator applied to 18th century paintings is justified because the overall uncertainty is small compared to the expected ASLR on the long term. In the short term and with real photographs, the ASLR is relatively modest and the uncertainty too large. In such a case, the method is acceptable only after 1872 (i.e. when the tide level is known) and if the date of the picture is known so that the reference is made to the estimated algal level and the uncertainty disappears. The method has been tested on early photographs taken in the period 1880-1890 but without indication of the precise date, and in this case the uncertainty for the algal belt fluctuations and other errors is 1/4 of the observed ASLR. The test performed with early photographs gave results coherent between them, and falling within the expected interval documented by the tide gauge observations, as we will see later. This confirms the reliability of this approach and suggesting that the uncertainty assumed is probably too large. More interesting results are expected from early pictures precisely dated in 1840s, when available.

Canaletto painted photographic views on the site, and also made duplicates in his studio. As replicas are suspected to be less reliable, in this study the earliest version of each view was pre-

ferred. In the absence of dating, the accuracy of the paintings having the same view was tested after comparison with the actual building. The test was performed by taking a quantitative evaluation of some architectonic details on the paintings, making comparison with the actual building and then computing the standard deviation of the error. The lower the standard deviation, the better the accuracy.

The CM level in the paintings was compared to the present-day situation with site inspections and measurements. A quantitative evaluation of CM displacement was possible by making reference to certain architectural features that constituted a useful frame within which to take and compare measurements (Fig. 2). The cases where building restoration has altered these architectonic features were discarded. Although Canaletto painted some 200 views of Venice, most of them cannot be utilized due to the absence of a view on a canal or because there is no clear indication of the algal belt, or because the old buildings have since been demolished or transformed. After a search in catalogues and collections, we found 17 potentially useful views, either in the original, or in a good reproduction. After inspection in Venice of the present-day conditions, the number of paintings available to us was reduced to 12, i.e. the only ones that reproduce buildings which have remained unaltered since the 18th century.

Fig. 2. Apparent Sea Level Rise (ASLR) in Venice from Canaletto and Bellotto paintings. Bellotto, S. Giovanni e Paolo (1741), detail (right). The two arrows give the level of the algal belt in 1741 (lower) and today (upper) as derived from on-site observations. The painting shows that there were two front steps above the green belt. The displacement is 77±10 cm. (left) The same door today. The picture was taken during low tide and the top step of the old front stairs is just visible (red arrow). The door was walled up with bricks in the first 70 cm above the front step to avoid water penetration (after Camuffo and Sturaro, 2003).

An analysis of the paintings (Camuffo and Sturaro, 2003, 2004) showed that the CM has risen on average by $\Delta CM_{obs} = 69\pm11$ cm since the first half of the 18th century (Fig. 3). The largest errors occurred when the green line was superimposed on a local frame and did not allow a fine resolution (e.g. uncertainty over the height of a step or a brick row). In this case, the uncertainty was resolved by the actual height of the step or row. In other circumstances, where the position of the algae was measured as a distance from an architectonic reference, e.g. a floor or a window, the uncertainty derived from the errors made in measuring these distances both on the site and in the paintings.
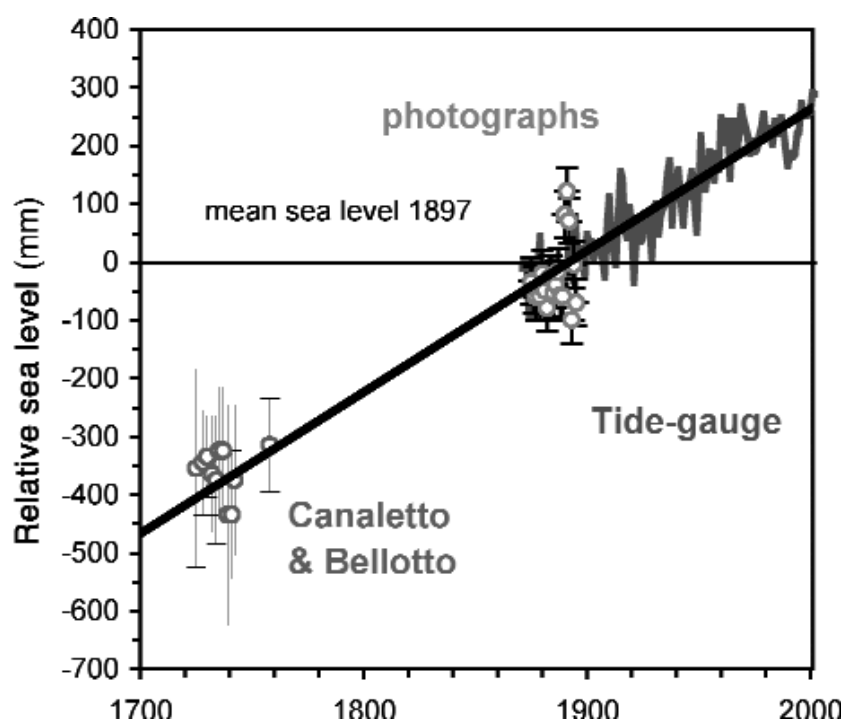
Fig. 3. Apparent Sea Level Rise (ASLR) in Venice from tide gauges (continuous blue line, period 1872-2002), from Canaletto's and Bellotto's paintings (red dots with error bars, period 1727-1758) and from early photographs (range dots, period 1880-1890). ASLR from paintings (and photographs) was estimated from the difference in level of the algae belt as it was in the paintings and as it is today.

One question was whether Canaletto and Bellotto were accurate in drawing the exact position of the algal front. The answer is given by the scatter of all the data: the better their accuracy, the smaller the scatter. The scattering of the data is limited to 12 cm, part of this being explained by the uncertainty in reading certain details, part by the yearly fluctuations of the CM, and possibly the individual response of building foundations. This confirms the reliability of the paintings and the consistency of the method.

The paintings were first analysed to check their accuracy in reproducing all details. Two kinds of details can be controlled: the architectural and decorative features of buildings making a cross comparison with the present day situation. When the algal belt falls in correspondence of a recognisable detail, it is possible to measure on the site how much the present day level is above that detail. This kind of measurement is of course independent from any distortion of the image. If the algae belt falls in the mid of a recognizable stone in the painting, the limit of uncertainty is connected with the precise evaluation of the proportion of stone covered with algae in comparison with the part free. Once this has been established, it is possible to measure the algae displacement on the site. In this case the uncertainty is a fraction of the brick or stone size, and depends on the size of the detail in the painting. For instance, in the case of algae apparently covering half of a typical brick row, 8 cm width, the maximum error is ± 4 cm.

Another test is based on the cross-comparison between the size of the architectonic features as they appear in the painting and in a picture of the actual building today. This is obtained from the ratio of the size of the corresponding items and then calculating the standard deviation of each series, as follows. For each painting, the building is divided into a number of strips corresponding to natural partitions of the facade, and the width of each strip is normalised expressing it as a fraction of the total building height. The same is made with a picture of the building today. Then the ratio is computed between each normalised size in the painting and the corresponding size in the picture of the building today, obtaining values close to, but slightly different from 1. It is finally possible to calculate the standard deviation of these ratios for each painting. The smaller the standard deviation, the better the accuracy (Camuffo and Suraro, 2003; Camuffo *et al.*, 2004).

The observed algal shift is primarily determined by ASLR and, secondarily, by wave height change. Waves generated by motor boats have a typical height of some 10 cm that is about twice the value of those generated by an 18th-century row-boat, as estimated from wave observations in the Grand Canal under differing conditions, motor traffic being either allowed or forbidden (Canestrelli and Cossutta, 2000). This is equivalent to an apparent 5-cm CM rise. Another factor is the amplitude of the tidal wave. After the excavation of two deep channels, the ingress of sea water into the Lagoon was facilitated, slightly amplifying the tidal wave in Venice. Analysis of tide gauge observations demonstrated that this dynamic effect contributes to the yearly average tidal amplitude raising the CM by another 3 cm. The combination of both the above factors gives an ASLR contribution equal to DASLRwave = 8±1 cm.

After this correction, the estimated relative sea level change since the Canaletto's time is 61±12 cm with average trend 2.3±0.4 mm yr^{-1}. This trend is close to that computed for the instrumental period 1872-2000, which was 2.4±0.1 mm yr^{-1}.

CONCLUSIONS

The apparent sea level is substantially raised with the same rate in the last three centuries, as confirmed by Canaletto's and Bellotto's paintings. The bulk estimate from the paintings is 2.3±0.1 mm yr-1 which is very close to 2.4±0.1 mm yr-1 found after the tide gauge records from 1872.

Venice submersion is explained in terms of three main causes. The first is the natural subsidence due to tectonic movements in the deep layers. This is worsened by the compaction of clay and peat sediments, although over the past centuries attempts have been made to reduce lagoon sediments and compaction by diverting rivers. During the Holocene, the tectonic subsidence in this area was estimated to be around 1 mm yr^{-1} i.e. from 0.7 to 1.2 mm yr^{-1} (Bondesan *et al.*, 2001; Carminati *et al.*, 2003). The second cause is the local anthropogenic land subsidence. The main factor was pumping of ground water from the upper aquifers for industrial purposes. In the period 1930-1970, highly affected by water pumping, subsidence was estimated to be 10-12 cm in comparison with sea level in Trieste (Teatini *et al.*, 1995; Carbognin and Taroni, 1996; Pirazzoli and Tomasin, 1999). If the intensive sinking 1930-1970 is removed, the estimate of the natural ASLR is 1.9±0.5 mm yr^{-1} in agreement with instrumental data for the early period 1872-1930. However, the apparent sea level always fluctuated around the main trend. An acceleration is evident in the period 1930-1970, followed by a deceleration. An apparent immediate benefit was due to a number of factors. One is a small aquifer rebound after 1970, estimated 1-2 cm. Other factors are connected with the eustatism, as follows. The third cause of submersion is the sea-level change (eustatism) in the Mediterranean which has been estimated to be 1.1-1.5 mm yr^{-1} in the last century, with a negative trend after 1960 (Tsimplis and Baker, 2000). This rate is smaller than that known on the global scale for three reasons that have characterized the last decades. First, the precipitation in the Mediterranean catchment area has decreased and the evaporation increased (Piervitali *et al.*, 1998). Second, the balance with the Black Sea has changed after the water of its tributaries has been substracted for irrigation purposes. Third, the atmospheric pressure over the Northern Adriatic has increased by 1 hPa, which is equivalent to 1 cm sea level depression.

The result of this study suggests that in Venice natural land subsidence, which is substantially constant (Teatini *et al.*, 1995; Bondesan *et al.*, 2001; Carminati *et al.*, 2003) and the eustatism in the Mediterranean (Tsimplis and Baker, 2000) had the same order of magnitude during the last three centuries.

The Venetian palaces, either on canals or streets, were originally protected against groundwater rise by a belt of non-permeable Istrian stone Now, after the city has sunk, the protective belt is too low and the flooding waters reach brick and plaster which are destroyed by salt crystallisation cycles. The municipality has introduced mobile footbridges (Fig.4) to make possible walking on flooded streets. This has partially solved the problem of pedestrian traffic. The main problem, i.e. to save buildings, is still open although a project to install mobile gates and to undertake other mitigative measures is underway.

Fig. 4. Mobile footbridges near Frari church to make possible walking on flooded streets during acqua alta.

La transgression finiglaciaire, l'archéologie et les textes (exemples de la grotte Cosquer et du mythe de l'Atlantide)

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La transition climatique de la dernière glaciation vers les conditions interglaciaires actuelles s'est accompagnée de changements spectaculaires des paysages côtiers ennoyés par la remontée de la mer. On commence à cerner les conséquences considérables de ces évènements quelquefois catastrophiques pour les populations préhistoriques. Le but de cet article est de présenter deux types de témoignages. L'enregistrement géologique et archéologique est illustré par le cas exceptionnel et indiscutable de la grotte Cosquer à Marseille. Le mythe de l'Atlantide renvoie, de façon plus spéculative, à l'enregistrement par l'homme des évènements survenus dans le Détroit de Gibraltar 9000 ans avant notre ère.

LA SUBMERSION DE LA RADE DE MARSEILLE ET LA GROTTE COSQUER

Le réchauffement climatique qui achève la dernière glaciation s'accompagne d'une fonte accélérée des glaces polaires suivie d'une remontée saccadée du niveau marin: 135 m depuis le dernier maximum glaciaire de 19 000 B.P. Les étapes de cette transgression sont maintenant bien connues grâce aux forages effectués ces vingt dernières années dans les récifs coralliens tropicaux (Barbades, Tahiti, Nouvelle-Guinée). Les courbes publiées (Bard *et al.*, 1990a et b; Bard *et al.*, 1996; Lambeck et Bard, 2000) traduisent une submersion régulière avec deux périodes de débâcles glaciaires accélérées où la remontée de la mer atteindrait 4 m par siècle (Fig. 1).

Au maximum glaciaire (19 000 B.P.), la mer se trouve à -130/-135 m (Yokohama *et al.*, 2000). La remontée de la mer s'amorce ensuite (Fig. 1) pour atteindre le niveau des -100 m à 14 000 avant le présent, période où elle s'accélère brutalement (Melt Water Pulse 1A). La mer remonte ensuite plus lentement jusqu'à la côte -55 m à 11 300 avant le présent, date d'une nouvelle accélération (Melt Water Pulse 1B).

On retrouve en rade de Marseille et sur le littoral des calanques les traces de ces évènements:

- Un carottage a intéressé un cordon littoral au sud du phare de Planier (Collina-Girard *et al.*, 1996). Age (132080+/-200 BP) et bathymétrie (90-95m) semblent correspondre au Meltwater pulse 1A.

- Le "tombant" de -55m, observé en plongée (surplombs et grottes littorales) est au niveau du trait de côte de 14 000 BP prévu par les courbes. Ceci a été confirmé par la datation de concrétions algaires littorales fossiles dont le début de la formation a été estimé à 9000 BP (Sartoretto *et al.*, 1995a).
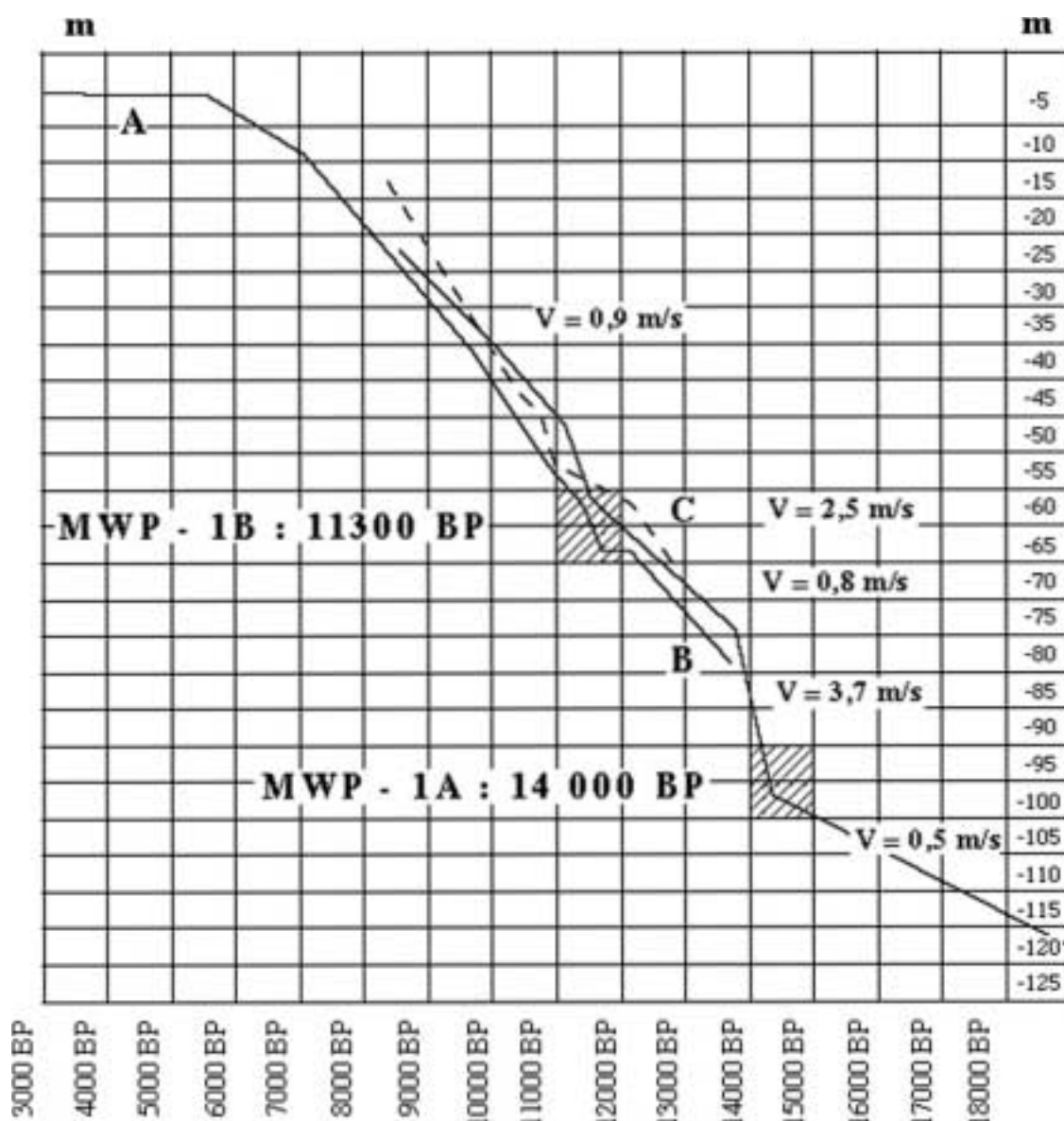
Fig. 1. Courbes de remontée du niveau marin depuis 19 ka BP., dates calendaires d'après trois forages en récifs coralliens (A-Tahiti, B-Barbades, C-Nouvelle Guinée., MWP-1A et B : Phase de débâcles glaciaires(Meltwater pulse 1 A et B). V=vitesses de remontée par siècle (Bard *et al.*, 1990a,b, 1996).

Les observations, en plongée suggèrent une remontée de la mer plus saccadée que celle révélée par les courbes tirées des récifs coralliens puisqu'on retrouve depuis Marseille et la Méditerranée occidentale jusqu'aux Caraïbes une séquence de platiers sous-marins, d'encoches ou de paléolagons noyés probablement holocène (Collina-Girard, 2002).

Au maximum glaciaire, il y a 19 000 ans, le plateau continental jusqu'aux grands canyons de Planier et de la Cassidaigne (Fig. 2) était émergé et fréquenté par les hommes du Paléolithique supérieur (Collina-Girard, 1992, 1995a). La grotte Cosquer, sanctuaire préhistorique majeur découvert au cours de l'été 1991 par un plongeur de Cassis (Cosquer, 1992) en témoigne de façon évidente (Clottes et Courtin, 1994).

LA GROTTE COSQUER : ARCHÉOLOGIE

Submergé par la remontée marine postglaciaire, le site n'est accessible qu'en plongée, par un siphon dont l'ouverture se trouve à -37 mètres de profondeur, à une quinzaine de mètres de la
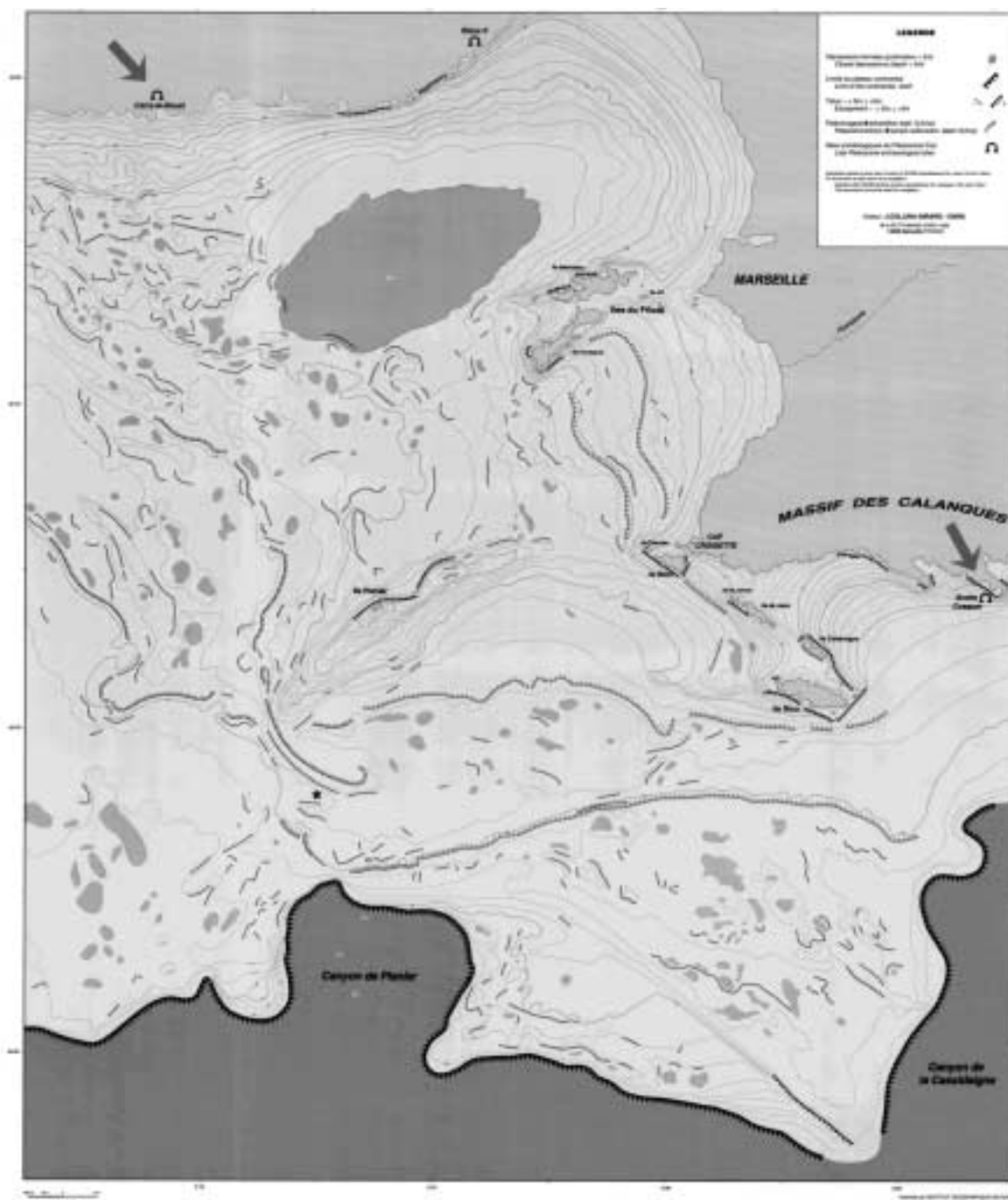
Fig. 2. Bathymétrie du plateau continental au large de Marseille, entre la Grotte Cosquer et le site préhistorique de Carry le Rouet, indiqués par des flèches rouges(Collina-Girard, 1995e).

côte. Les peintures sont intactes au-dessus du zéro actuel de la mer. Les datations C14 ont confirmé la chronologie stylistique en prouvant deux phases d'occupation, à 26500/27500 B.P. (phase 1) et 18 500/19 500 BP (phase 2) (Clottes et Courtin, 1994; Clottes *et al*., 1996a,b; Clottes *et al*., 1997; Collina-Girard, 1995d, 1998).

Phase 1 : vers 27 000 B.P.

À cette phase ont été attribués les milliers de tracés digitaux qui couvrent les parois calcaires ramollies par le mondlich. On les trouve dans des recoins et des diverticules peu accessibles, et aussi sur des plafonds qui n'ont pu être atteints qu'en escaladant certains piliers stalagmitiques.

Cette phase comprend aussi des mains négatives, à présent au nombre de 55, groupées en deux panneaux principaux.

Phase 2 : 19200 B.P. à 18 500

La plupart des peintures (principalement des dessins au charbon) et des gravures (actuellement 125) sont à rapporter à cette tranche chronologique. La plupart des animaux sont gravés, moins d'un tiers sont peints. Le cheval domine de loin, suivi des caprinés (bouquetins, chamois), des bovinés (bisons, aurochs), des cervidés (cerf élaphe et grand cerf mégacéros). Les phoques gravés et les pingouins tracés au charbon sont une des originalités du site. De nombreux signes géométriques ont été notés en 1992, d'autres trouvés en 1994. Plusieurs, rectangulaires, surchargés de triangles ont été désignés par les termes de signes "en valise" ou "en enveloppe". Ils sont spécifiques à la grotte Cosquer (Clottes *et al*., 1997). Figurent aussi des représentations de sexes : vulves possibles et nombreuses et un phallus découvert par J. Courtin en 1994 (Clottes *et al*., 1997). Une gravure surchargée de profondes incisions a été interprétée par Jean Clottes comme une représentation chamanique, "homme-phoque", "tué" par une arme de jet (Clottes et Courtin, 1994).

LA GROTTE COSQUER : NÉOTECTONIQUE ?

De nombreuses chutes de concrétions ont été observées. Elles accompagnent le cisaillement ou l'écrasement de plusieurs piliers stalagmitiques dans le sens du pendage des assises urgoniennes. Tous ces indices semblent indiquer des mouvements gravitaires vers le sud. Cette cavité est évidée dans un inter-banc et son toit à peine soutenu. L'ensemble semble instable et à la merci de la moindre modification de l'équilibre de la masse rocheuse. Les fragments de concrétions, profondément soudés aux planchers stalagmitiques, témoignent de l'ancienneté de réajustements que l'archéologie permet de situer entre les deux phases d'occupation de la grotte (Collina-Girard, 1995b,c; Collina-Girard, 1996). En effet :

- Les draperies aux mains négatives noires de la phase ancienne sont partiellement désolidarisées du plafond par des mouvements qui leur sont postérieurs.

- Certaines concrétions tombées du plafond et ressoudées au sol ont servi de supports aux petits foyers d'éclairage de la phase récente.

Les études néotectoniques conduites en Provence ont mis en évidence une importante phase sismique régionale. Cet évènement a été daté sur les terrasses alluviales dans la vallée de la Durance (Sébrier *et al*., 1997) entre 26 800 B.P. +/- 610 années B.P. et 9123 +/- 190 années BP. L'évènement sismique serait unique plutôt que progressif avec une magnitude de 6,4-6,9. Cette période pourrait coïncider avec celle des écroulements observés à la grotte Cosquer. L'archéologie donnerait alors un argument de datation aux néotectoniciens pour préciser la période où ce séisme se serait produit en rétrécissant la fourchette de temps entre 27 000 et 18 000 B.P. L'hypothèse d'une phase sismique entre 27 000 et 18000 B.P. expliquerait alors l'interruption de l'occupation de la grotte constatée pendant 9000-10 000 ans.

PRÉHISTOIRE ET REMONTÉE DE LA MER

La partie supérieure du site est la seule conservée. Les trois quarts inférieurs de la grotte ont été noyés par la remontée marine finiglaciaire. Les peintures, intactes au-dessus du niveau de la mer, sont incompatibles avec une remontée de la mer au-dessus du zéro actuel. Les courbes (Bard *et al*., 1990a,b, 1996; Lambeck et Bard, 2000) indiquent que la fermeture de la grotte (-37m) a pu se produire au cours du 10e millénaire avant le présent. Cette période de submersion a été précisée par la datation de deux concrétionnements coralligènes prélevés à l'entrée du siphon, au contact du substrat rocheux. Compte-tenu de la répartition bathymétrique des espèces présentes, la date de la submersion de l'entrée du siphon (-37 m) a été estimée vers 7000 B.C (fin du Mésolithique ou début du Néolithique cardial) (Sartoretto *et al*., 1995b).

Le témoignage archéologique de la grotte Cosquer illustre une évidence : l'homme préhistorique a subi, à la fin de la dernière glaciation, une remontée de la mer sensible et mondiale. On sait que cette modification, parfois brutale, du trait de côte s'est accompagnée de changements climatiques et culturels majeurs. La tradition orale a-t-elle transmis le souvenir de ces événements jusqu'aux premiers écrits ?

PRÉHISTOIRE ET TRADITIONS ORALES

La préhistoire des chasseurs-cueilleurs montre des conservatismes qui impliquent la transmission de traditions pendant des millénaires. L'art préhistorique européen reste quasiment inchangé pendant plus de 20 000 ans. Dans la grotte du Parpallo près de Valence (Espagne), Jean Clottes a relevé la récurrence de rites immuables pendant 10 000 ans (offrandes répétées avec 4500 plaquettes gravées ou peintes dans des couches allant du Gravettien au Magdalénien final). Comme le constate ce spécialiste de l'art pariétal : "ces comportements témoignent de façon indiscutable de la persistance de la même tradition religieuse sur dix millénaires" (Clottes, communication verbale).

Au Canada, on a pu corréler des évènements géologiques (glissements de terrains, éruptions volcaniques, assèchements de lacs) aux mythes des indiens Gitksans. Les événements dont il est question ont eu lieu entre 6000 B.P. et 10 000 B.P. Les Indiens renvoient couramment à un temps avant ou après le déluge ("Before the flood" ou "Soon after the flood"; Harris, 1997) se référant au premier peuplement de leur territoire, libéré des glaces à la fin du Pléistocène et au début de l'Holocène

Plus près de nous, le récit d'Homère de la guerre de Troie a longtemps été considéré comme un mythe. Pourtant les archéologues sont actuellement unanimes à admettre son fondement historique. Des études géologiques récentes ont montré que la reconstitution paléogéographique des paysages s'ajuste parfaitement au récit homérique (Kraft *et al.*, 2003).

LA GÉOLOGIE ENREGISTRÉE PAR LE MYTHE DE L'ATLANTIDE ?

Vers le VIIe siècle B.C., la Bible transcrit des traditions orales plus anciennes. Elle se fait l'écho de faits historiques et probablement de faits géologiques plus anciens. Le récit du Déluge pourrait renvoyer à des inondations catastrophiques comme celle attestée en mer Noire (Ballard *et al.*, 2000; Fortey, 2000; Lericollais *et al.*, ce volume). Un peu plus récemment, au IVe siècle B.C., Platon écrit le Timée et le Critias (Rivaud, 1956). Il affirme développer son Utopie de l'Atlantide à partir d'un fait réel. Platon, grand voyageur, avait pris connaissance, en Egypte et en Sicile de légendes et de faits historiques sur le bassin occidental de la Méditerranée et peut-être des régions océanes (Bourra, 2003). Selon les prêtres de la ville de Saïs en Egypte, un archipel habité aurait été englouti au débouché atlantique des Colonnes d'Hercule (le Détroit de Gibraltar) 9000 ans auparavant.

Curieusement la reconstitution géographique du paysage du maximum glaciaire devant le Détroit de Gibraltar (Collina-Girard, 2001) fait ressurgir une île et un archipel actuellement sous la mer (Fig. 3). Ce paysage et son histoire coïncide point à point à celui décrit par Platon.

Timée : "En effet, en ce temps-là, on pouvait traverser cette mer. Elle avait une île, devant ce passage que vous appelez, dites-vous, les colonnes d'Hercule." (Rivaud, 1956: 26b).

Géologie : A l'ouest du Détroit de Gibraltar une mer intérieure précédait l'Océan Atlantique. On pouvait facilement traverser cette mer pour atteindre les continents africains et européens. Une île, actuellement immergée faisait face aux "colonnes d'Hercule" (Fig. 4).

Timée : "Car d'un côté, en dedans de ce détroit dont nous parlons, il semble qu'il n'y ait qu'un havre au goulet resserré et, de l'autre, au-dehors, il y a cette mer véritable et la terre qui l'entoure et que l'on peut appeler véritablement, au sens propre du terme, un continent." (Rivaud, 1956: 25b).

Géologie : La description de Platon pourrait s'appliquer sans modifications à la conformation du détroit de la période glaciaire (Fig. 3). La passe Est (en dedans par rapport à la Méditerranée) se présente comme un couloir très étroit ("un havre au goulet resserré"). La partie ouest est une véritable mer intérieure (77 km de long pour une largeur de 10 à 20 km). Cette Méditerranée en miniature était entourée par les continents africains et européens élargis par l'émersion de leurs plateaux continentaux respectifs.
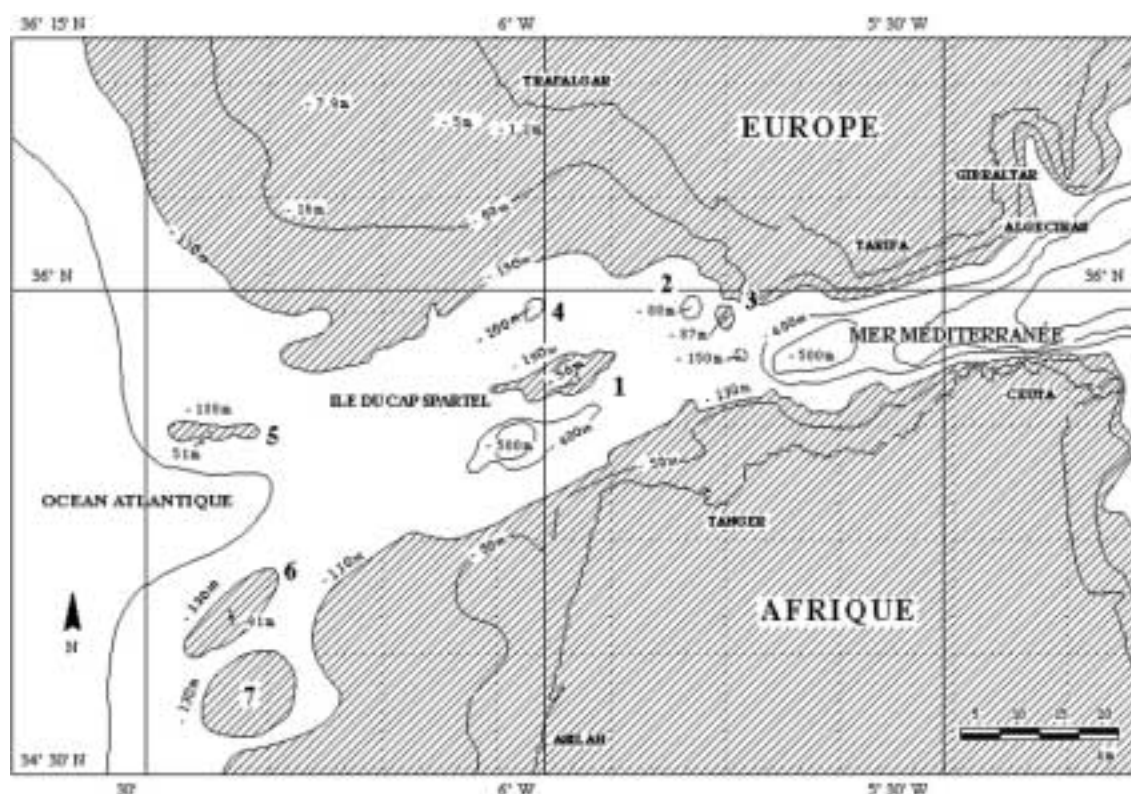
Fig. 3. Paléogéographie du Détroit de Gibraltar à 19-21 Ka B.P. (zones émergées en hachures). 1,2,3,4, 5, 6, 7 : îles et îlots , (1 : île du Cap Spartel). 7 - île submergée à 19 000 B.P., 2, 3, 4, 6 : îles submergées à 14 000 B.P., 1 et 5 : îles submergés à 11 000 B.P. (Collina-Girard, 2001).

Timée : "Et les voyageurs de ce temps-là pouvaient passer de cette île sur les autres îles, et de ces îles, ils pouvaient gagner tout le continent, sur le rivage opposé de cette mer qui méritait vraiment son nom." (Rivaud, 1956: 25b)

Géologie : A partir de cette île, on pouvait passer sur les autres (Fig. 3, 5-6-7) et gagner ensuite le continent au nord ou au sud après avoir traversé une mer quasi fermée (à l'ouest par une barrière d'île) de 77 km sur 20 km (mer "qui mérite vraiment son nom "). Proclus (Ve siècle de notre ère) cite pour sa part, un géographe, Marcellus, qui mentionnerait lui aussi une dizaine d'îles disparues devant le Détroit de Gibraltar (Proclus, commentaires sur le Timée, Tome premier, livre 1, traduction Festugière, 1966, p. 233).

Timée : "Cette île était plus grande que la Libye et l'Asie réunies". (Rivaud, 1956: 25b)

Géologie : A première vue, il s'agit du seul point dissonant puisque la dimension donnée par Platon est sans commune mesure avec celle de l'île du Cap Spartel et des autres îles de l'Archipel. On peut toutefois relever dans le Critias une indication contradictoire, ou alors ce n'est plus la dimension de l'île Atlantide dont on parle mais celle de l'étendue du territoire des Atlantes : " … Non seulement étaient-ils maîtres de plusieurs autres îles dans la mer mais encore, comme il a été dit antérieurement, leur pouvoir s'étendait sur les régions qui se trouvent en deçà des colonnes d'Héraclès, jusqu'en Egypte et à la Tyrrhénie" (Brisson, 1999: 364).

Cette description pourrait alors s'appliquer au territoire des populations préhistoriques qui avaient envahi les côtes du Maghreb des Colonnes d'Hercule à la Tunisie pendant que leurs homologues européens se répandaient sur les côtes du continent européen jusqu'à la Tyrrhénie (et bien au-delà !).

On sait aussi que les navigateurs et historiens antiques ne disposaient d'aucun moyen sûr de mesures et de relevé de positions et surestimaient toujours distances et surfaces. La mer Noire d'Hérodote est trois fois trop grande, Néarque exagère considérablement son itinéraire dans l'Océan Indien, Pythéas les dimensions de la Grande-Bretagne (Foex, 1964). Peut-être faut-il

plus simplement supposer une certaine dérive magnifiante, au cours de 9000 ans de transmission orale ? L'a priori de Platon voulant magnifier la puissance qu'il oppose aux anciens grecs dans sa fiction n'est peut-être pas étrangère à cette exagération.

Les commentateurs antiques eux-mêmes ne semblaient pas prendre au sérieux les dimensions que Platon attribuait à l'île Atlantide. Proclus explicite pour nous ce point particulier : "Il faut ici se rappeler les principes fondamentaux de Platon sur la terre, à savoir qu'il n'en mesure pas la grandeur de la même manière que les mathématiciens, mais a estimé qu'elle a plus grande étendue, comme le dit Socrate dans le Phédon, et pose qu'il y a bien d'autres lieux de séjour à peu près égaux à notre terre habitée. C'est pourquoi il rapporte l'existence dans la mer extérieure, d'une île et d'un continent d'une telle ampleur (Proclus, commentaires sur le Timée, Tome premier, livre 1, traduction Festugière, 1966, pp. 236-237).

Timée : "C'est donc de vos concitoyens d'il y a neuf mille ans que je vais vous découvrir brièvement les lois" (Rivaud, 1956: 23e).

Géologie : Cette date (11 Ka B.P.) coïncide exactement avec celle de la submersion des deux îles majeures de l'archipel du Cap Spartel. La mer atteint la cote - 55 m vers 11 Ka B.P. (Fig. 1): c'est, curieusement, la date exacte indiquée par Solon qui n'avait pourtant aucune connaissance des étapes de la remontée de la mer finiglaciaire ! Cette exactitude troublante est peut être pure coïncidence, mais il faut rappeler que dans les sociétés sans écriture le décompte des généalogies est très pratiqué avec des exemples de lignées apprises par cœur pendant plus de mille ans dans des sociétés africaines (Podlewski, 1993). Les Égyptiens enregistraient les évènements et les dynasties depuis plus de 3000 ans (Lefort, 1998). Ils pouvaient fort bien avoir enregistré les listes généalogiques des sociétés antérieures et accéder à une chronologie au moins approchée des évènements.

Timée : "Mais, dans le temps qui suivit, il y eut des tremblements de terre effroyables et des cataclysmes. Dans l'espace d'un seul jour et d'une nuit terribles, toute votre armée fut engloutie d'un seul coup sous la terre, et de même l'île Atlantide s'abîma dans la mer et disparut. Voilà pourquoi, aujourd'hui encore, cet océan de là-bas est difficile et inexplorable, par l'obstacle des fonds vaseux et très bas que l'île, en s'engloutissant, a déposé." (Rivaud, 1956: 25d).

Géologie : En dehors de la certitude d'une submersion accélérée du paléodétroit et de son archipel, contemporaine du basculement vers les conditions interglaciaires actuelles, il n'est pas exclu que des phénomènes sismiques ou des raz de marée se soient produits dans la même fourchette temporelle comme le montrent les exemples historiques (Silva *et al*., ce volume).

Le séisme du 1er novembre 1755 (intensité 10-11 sur l'échelle de Mercalli) dont l'épicentre était sous-marin, a partiellement détruit la ville de Lisbonne et déclenché un raz-de-marée sur les côtes portugaises et marocaines. Les vagues de ce raz-de-marée ont atteint plus de 6 mètres à Lisbonne, plus de 5 mètres au Cap St Vicente (SW Portugal) et plus de 10 mètres tout au long du Golfe de Cadiz (Baptista *et al*., 1998).

Timée : Platon développe ensuite la fiction d'une République Idéale opposée victorieusement à l'envahisseur. L'auteur avertit son lecteur du caractère imaginaire de cette utopie : "Les citoyens et la cité qu'hier vous nous avez représentés comme une fiction, nous les transposerons maintenant dans l'ordre du réel : nous supposerons qu'il s'agit de la cité que voici : les citoyens que vous aviez imaginés, nous dirons que ce sont ceux-ci, les vrais, nos ancêtres, ceux dont avait parlé le prêtre. Il y aura concordance complète, et nous n'errerons point si nous affirmons qu'ils sont bien ceux qui existèrent en ce temps-là." (Rivaud, 1956: 26d).

Géologie : Si la complexe société atlantidienne du Critias est imaginaire, il n'y a aucune contradiction à relier le Timée aux événement naturels paroxystiques de la fin du Paléolithique.

La Géologie prouve donc la réalité d'une île engloutie 9000 ans avant Platon devant le Détroit de Gibraltar (les Colonnes d'Hercule). Cette "Atlantide" réelle, au débouché du Détroit de Gibraltar, serait-elle le noyau originaire de "l'Atlantide" de Platon ? L'engloutissement des œuvres d'art de la grotte Cosquer montre très concrètement la submersion de ces "mondes per-

dus" évoqués par les auteurs de science fiction du XIXe siècle. L'histoire oubliée des chasseurs-cueilleurs de la fin du paléolithique et du néolithique aurait donc laissé, en dehors des vestiges archéologiques, quelques vestiges littéraires, échos lointains de scénarios réellement catastrophiques: submersion brutale de la mer Noire (Ballard *et al.*, 2000; Lericolais *et al.*, ce volume) ou engloutissement d'un archipel habité dans le proche Atlantique (Collina-Girard, 2001). La question de l'enregistrement d'évènements géologiques majeurs par la tradition orale et les mythes reste difficile. Elle nécessite une analyse critique des sources et une base géologique assurée. On trouvera dans ce volume plusieurs contributions qui tentent de confronter données géologiques et textuelles (Lericolais *et al.*; Petit-Maire; Wyatt; Sakellariou et Lykousis; Brückner). Le cas de l'Atlantide montre que l'on peut avoir de bonnes présomptions sans jamais pouvoir écarter totalement l'hypothèse de la coïncidence, la démonstration absolue étant malheureusement inaccessible !

Impacts of historical seismicity on major ancient coastal cities in southwestern Turkey

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INTRODUCTION

Active tectonics played an important role on the landforms of Western Turkey, one of the most tectonically active regions of the world. The region is currently experiencing roughly NNE-SSW stretching (McKenzie, 1972) which has given rise to a distributed horst and graben topography that characterises most of western Turkey (Fig. 1). Cnidus, Miletus, Priene and Ephesus were major ancient cities on the Aegean coast (Fig. 2) and grabens were important routes for people and armies travelling either from west or east between these coastal cities and interior cities in Anatolia. Thus, this region of the World has attracted settlers from very early times and inhabitation of the area extends back at least 3000 years.
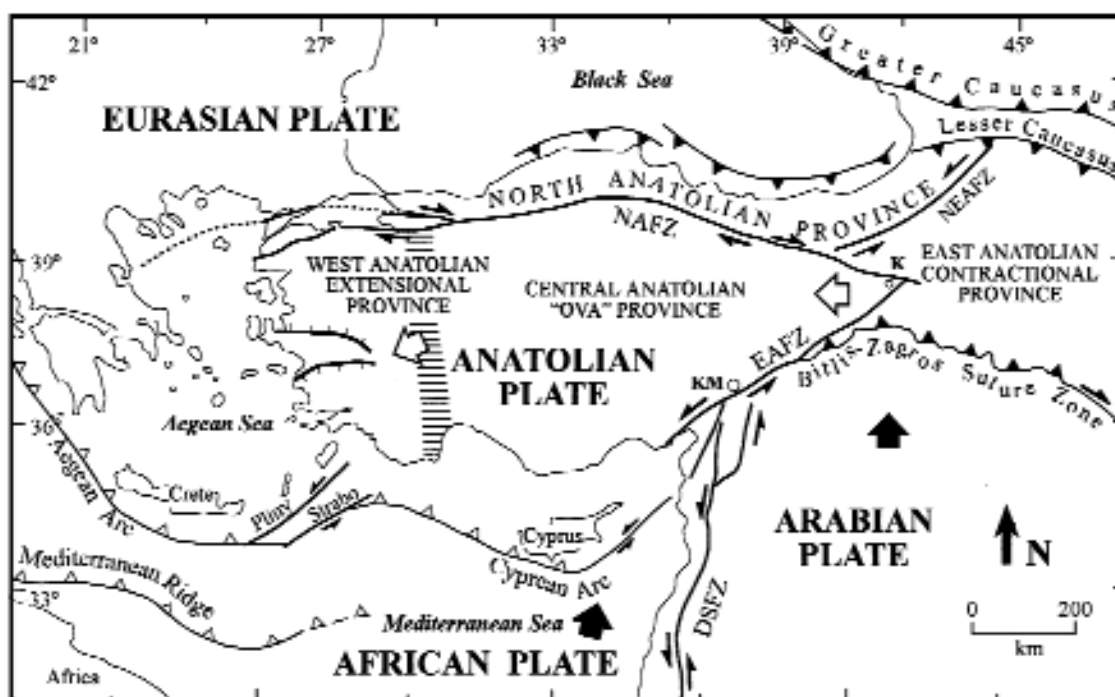

Fig. 1. Neotectonic map of Turkey (from Bozkurt, 2001).

Fig. 2. Main active faults and locations of major ancient cities in western Turkey.

Recent examples such as the 1999 Izmit and Düzce earthquakes show that in tectonically active regions, damaging earthquakes play a certain role in the history of a settlement as man-made structures are damaged due to both rupturing along a fault or fissures, and widespread ground shaking. There are some examples in Turkey (such as Balat, Gediz, Dinar) where after a damaging earthquake, the settlement either was shifted or reconstructed with help from the government.

The horst-graben system of western Turkey contains active normal fault geometric segments that have ruptured during major events in the historical period. Likewise, large historical earthquakes have affected ancient cities which were active at that time, besides causing damage to man-man structures they played important role in the history of settlement. This paper describes seismic damages in the coastal ancient cities of Cnidus, Miletus, Priene and Ephesus and discusses impacts of large earthquakes on these cities.

HISTORICAL BACKGROUND

Although it is not known when the first settlement was established in southwestern Turkey, it is evident that the warm climate, fertile lands, abundance of water, geographic position and the morphological configuration of western Turkey attracted settlers from very early times. Before the Persian occupation of the region in 545 B.C., there were several small kingdoms in southwestern Turkey (Akurgal, 1995). The region was occupied by Alexander the Great in 333 B.C. before passing into Roman (~130 B.C. – 395 A.D.), Byzantine (395 A.D. – 1071) and finally Turkish hands.

Cnidus

Cnidus is located at the western extremity of the E-W-trending Resadiye peninsula which is a horst in the horst-graben system of western Turkey (Fig. 3).

The present site of Cnidus is not the original site of the city (Bean, 1971). The original settlement in this peninsula was established in early 7th century B.C. near the modern town of Datça, situated on a broad sheltered bay on the southern coast (see Newton, 1865; Grant, 1986; Bean, 1971). During the 4th century B.C. Cnidus was shifted from Datça to the present site.

Fig. 3. Location of the ancient city of Cnidus in southwestern Turkey (from Altunel *et al.*, 2003).

Cnidus was an important coastal city in southwestern Asia Minor. Cnidians earned revenue from their widespread export of wine as well as the production of onions, medicinal oils, vinegar, and reeds for pens. Cnidus was the birthplace of Ctesias, physician and historian of Persia and of the outstanding mathematician, astronomer and geographer Eudoxus who had an observatory at Cnidus, from which, he was able to observe the star of Canopus. Cnidus was abandoned after the 7th century A.D.

Miletus

Miletus, located at the southern margin of the Büyük Menderes graben (Fig. 4), was a coastal city with four harbours (see Brückner, this volume). It was one of the oldest and most important settlements in Ionia. Owing to the silting of the area by the Menderes River (the ancient Maeander River), the present-day town lies in the middle of the Menderes garben. The Greeks settled in the area as far back as the 10th or even the 11th century B.C. (Akurgal, 1995). Miletus became very prosperous in the 7th and 6th centuries B.C. when, owing to the establishment of ninety colonies on the Black Sea and the Mediterranean, became the metropolis of the Ionian world. The first steps towards the establishment of western culture, especially in the field of exact science, were taken mainly by the city of Miletus. The natural philosophers Thales, Anaximander and Anaximenes, the famous historian and geographer Hekataios, the town-planning architect, Hippodamos, and Isidoros, one of the designers of St. Sophia in Istanbul, were all native Milesians. Towards the end of the 5th century B.C., the Milesian alphabet was officially adopted by Athens and so became the standard writing system of the Greeks. Miletus lost its coastal city position after the Byzantine period as a result of alluvial deposition from the Menderes River Miletus was abandoned in the 20th century.

Priene

Priene is located in the northern margin of the Büyük Menderes graben (Fig. 4). Founded in the 10th century B.C., it was one of the earliest Ionian settlements but its present location is not the site where it was first founded (Duyuran, 1948; Baran, 1965: Bean, 1966; Akurgal, 1995). The first city was located on the coast about 8 km to the east of the present location. In 350 B.C., the new city of Priene was built on its present site with the financial help from Athens. The new
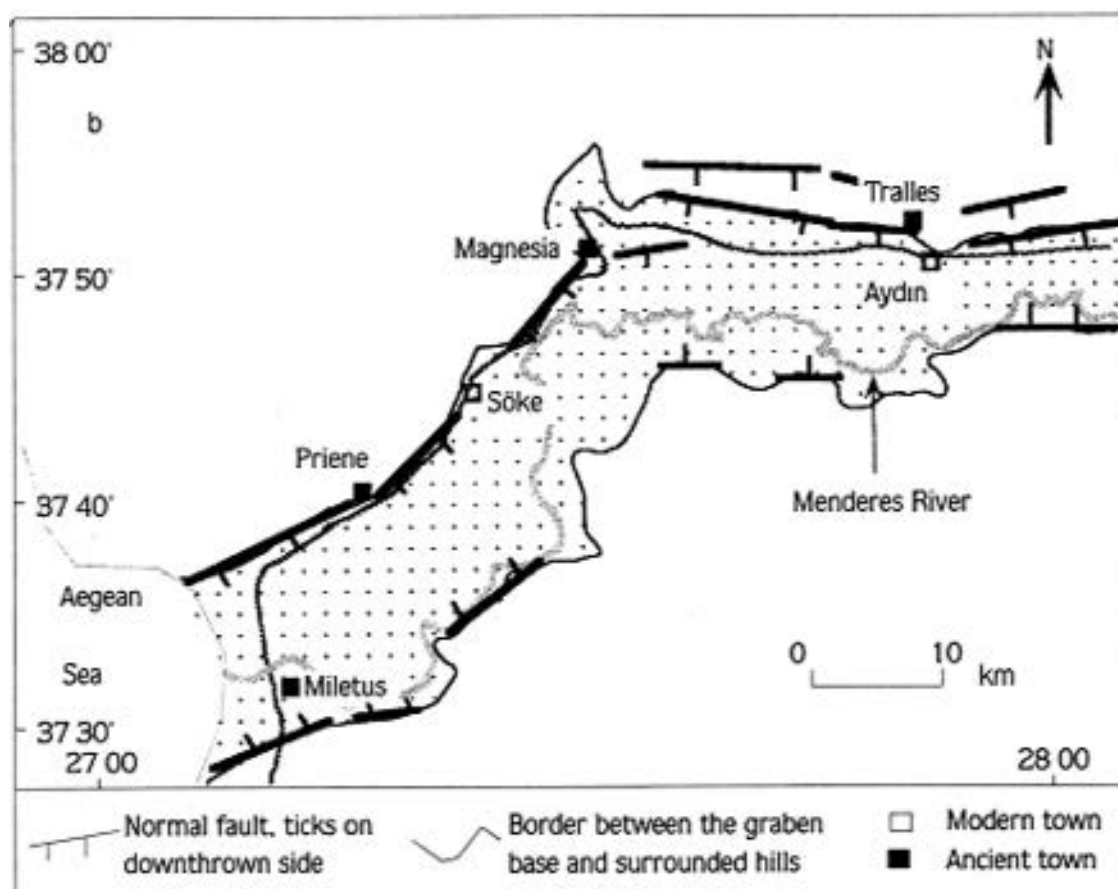
Fig. 4. Locations of the ancient cities of Miletus and Priene in southwestern Turkey (from Altunel, 1998).

Priene was also on the coast when first founded but the alluvial deposits brought down by the Menderes River gradually increased the distance between Priene and the Aegean Sea coast (Brückner, this volume). Bias, one of the most famous metaphysicians in the world, lived in Priene in the beginning of the 6th century B.C.. When Alexander the Great attacked Miletus in 334 B.C., he lived in Priene. It was the centre of an important diocese during Byzantine period. The city was abandoned at the end of the 12th century.

Ephesus

Ephesus was established around the 10th century B.C (Akurgal, 1995). It was the most prosperous commercial centre in the second century B.C. and controlled the banking affairs of the whole of western Anatolia. The city of Ephesus was referred to as the metropolis of Asia. After a period famous in ancient history for strife and upheaval, lasting throughout the 3rd century A.D. and subsequently to the middle of the 4th century, it entered into another golden age which continued until the Justinian era (527-565 A.D.). Ephesus enjoyed a further period of prosperity in the Seljuk era, 14th century.

DESCRIPTION OF SEISMIC DAMAGE

While the foundation of the ancient cities of Cnidus, Miletus, Priene and Ephesus goes back as far as the 2nd millenium B.C., existing ruins in these cities mainly date from the Roman and Byzantine periods. A few features from the Hellenistic period appear in these cities but nothing from the earlier eras. Some major buildings (such as bouleuterion, theatre, gymnasium, bath, temple, agora) are well-preserved in general but other constructions mainly collapsed and remains are partly covered by sediments. Buried archaeological remains have been excavated since at least 1850. Detailed field survey showed that these cities were damaged by large historical earthquakes; the most common damage is characterised in two forms in Cnidus, Miletus, Priene and Ephesus.

The first type presents the following characteristics: (1) columns of temples, streets, theatres etc. have fallen parallel to each other; (2) column drums are offset on each other; (3) columns are rotated and broken; (4) walls are tilted, and toppled; (5) bases of columns are rotated on each other; and (6) floor blocks of buildings and sitting rows of theatres and stadium are cracked and displaced. This type of damage is related to strong ground shaking (Fig 5) and is evident in Cnidus, Miletus, Priene and Ephesus.

Fig. 5. (a) Northern entrance to the theatre in Miletus. Note that walls are dilated. (b) A reconstructed street in Ephesus. Note that columns were used (red arrows) and they were not eroded as much as other block stones (blue arrows).

The second type of damage is related to ground rupture related; it includes faulted archaeological relics in Cnidus and Priene (Fig. 6). The Temple of Aphrodite Euploia in Cnidus offsets across an approximately E-W-trending fault. The southern part of the temple was downthrown up to 35 cm along the fault. A NE-SW-trending fault zone ruptures buildings in Priene where ruins are offset by about 50 cm vertically and about 5 cm dextrally.

Fig. 6. (a) Offset in the Temple of Aphrodite Euploia in Cnidus. The south side was downthrown about 35 cm. (b) Stoa in Priene, where the northwestern side was downthrown about 50 cm (red arrow) along a NE-SW-trending zone.

CONCLUSIONS

Some ancient buildings in Cnidus, Miletus, Priene and Ephesus are either offset by faults or ruptured by fissures. In addition, broken corners of blocks, collapsed walls, broken columns, tilted and toppled blocks are there to be seen, characteristic damage patterns of ground shaking. Similar damage has been reported from different parts of the world (e.g. Karcz and Kafri, 1978; Stiros 1996; Korjenkov and Mazor, 1999; Hancock and Altunel, 1997; Altunel, 1998; Piccardi, 2000; Akyüz and Altunel, 2001; Silva, this volume) and there is no doubt that deformation observed in ancient cities in southwestern Turkey is of tectonic origin.

The present sites of Cnidus and Priene are not the original sites. The reasons for shifting these cities westwards in the 4th century B.C. are not clear. Later on, although Cnidus and Priene were important cities, they were abandoned in the 7th and 12th century A.D., respectively. Comparing

the abandonment dates of these cities with other important cities in western Turkey, it is clear that they were abandoned early. Considering that ancient Cnidus and Priene were located directly on active normal faults, it is likely that the old cities were completely destroyed by earthquakes in the 4th century B.C. Rebuilt in their present sites, their abandonment centuries later was also related to earthquakes as both cities had been relocated on active faults.

No offsets are observed on ruins in Miletus and Ephesus. However, damage and major reconstructions in these cities show that they were affected by strong ground shaking of large earthquakes which occurred on adjacent active faults.

Archaeological and biological records of relative sea-level changes in the Mediterranean during the Late Holocene. Two case studies of gradual evolution to instantaneous events, Marseilles (France) and Pozzuoli (Italy)

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INTRODUCTION

Examples of different relative sea-level changes

On a *long-term* timescale (century to millennium), the study of late Holocene relative sea-level changes is important in assessing various non-eustatic dynamic factors (isostatic movements, tectonics, sea-surface topography...) that may have triggered local changes (Mörner, 1996). The precision of the bio-archaeological approach is significant in that the world-famous sea-level curves have been based, for the last 5-6 millennia, upon few measurements. For example, only two ages exist for the Tahiti coral reefs (Bard *et al.*, 1996), and four ages for the Barbados coral reefs (Fairbanks, 1989). Moreover, many of these dates are based upon reef-crest corals (Montaggioni *et al.*, 1997), which are low precision indicators (Laborel and Laborel-Deguen, 1996), since the vertical range of repartition in modern reefs has been of the same magnitude as relative sea-level variations over the last 5,000 years. This gradual slowdown can be recorded in the ancient harbour of Marseilles, founded 2,700 years ago, in a so called tectonically stable area.

On a *medium-term* timescale (month), relative sea-level changes can be linked to volcano-tectonic dynamics: this mobility is called bradyseism in Italy.

On an *instantaneous* timescale, for example, co-seismic sea-level movements result from the Early Byzantine Tectonic Paroxysm in the Eastern Mediterranean (Pirazzoli, 1986; Pirazzoli *et al.*, 1996a and b). Relative sea-level changes have shown that various vertical tectonic displacements – some of them of exceptional amplitude – took place between 1,750 and 2,000 years B.P. The area of the displacements extends from the Ionian islands and the Corinth gulf, through Crete to the Levant coasts. After calibration, the radiocarbon dates obtained correspond approximatly to the 6th century A.D. These movements could be linked to exceptional tectonic activity that occurred on a regional scale during Early Byzantine times. According to various historical earthquake compilations, this period appears as especially seismic in the Eastern Mediterranean (Guidoboni *et al.*, 1994). In Crete, the ancient harbour of Phalasarna was suddenly uplifted by ca. 10 m (Pirazzoli *et al.*, 1992; Dominey-Howes *et al.*, 1998).

Indicator reliability

Bioconstruction indicators provide quite precise palaeo-bathymetric data. Conversely, archaeological remains provide less precise palaeo-bathymetric measurements but more accurate chronological ages, which cannot be matched by radiometric methods. By definition, ancient harbours are protected environments, and therefore there is no obstacle to biological dynamic sea-level variations.

For example, interface structures are precise depth indicators. Amongst these, piers provide informative data, especially when compared to palaeo-biological zonation. Well measurements of water table levels are essentially linked to the local water budget (Sivan, this volume). Sewer base levels may show the limit of ancient shorelines. Slipways are often long lasting, and no architectural indicator clearly shows the palaeo-sea level (Vött, this volume). When one does not consider a biological approach, it may be fallacious to trust the precison of archaeological depth estimations.

GRADUAL RELATIVE SEA-LEVEL CHANGES IN THE ANCIENT HARBOUR OF MARSEILLES (FRANCE) OVER THE LAST 5,000 YEARS

Recent archaeological excavations of the ancient harbour of Marseilles (Morhange *et al.*, 2001) have yielded a set of very high precision data for the past 4,000 years. They fit those obtained on the same coasts, deriving from *Lithophyllum lichenoides* bioconstructions, with a precision of +/- 10 cm (Laborel and Laborel-Deguen, 1994).

The ancient harbour of Marseilles is a deep and narrow sheltered embayment in Oligocene conglomerates and sandy marls, surrounded by steep hills (Fig. 1). Tidal range is only about 0.1m. Marseilles is considered to have been a tectonically stable region during the late Quaternary (Collina-Girard, this volume).

Methodology

One of the various biological sea-level indicators used in the Mediterranean area includes the upper limit of barnacles. Thriving in polluted and confined environments, these organisms are well adapted to harbour areas (Pirazzoli and Thommeret, 1973; Laborel and Laborel-Deguen, 1994). It has long been shown (Pérès and Picard, 1964) that *Balanus* populations commonly develop upon quay walls, stopping abruptly at biological mean sea level.

Precision obtained from barnacles ranges from plus or minus a few centimetres, when the upper population limit is continuous, decreasing to ca. 10 cm when it is scattered. Wherever *Balanus*-bearing hard substratum was not available, the summit of beach sub-tidal onlap layers was used as a sea-level indicator (precision: +/-0.2 m).

Results

The oldest marine sedimentary unit is a sub-littoral pebble beach overlying the Oligocene substratum and reaching -1.64 m NGF (Nivellement Général de la France - Official reference datum in France). Pebbles bear fixed marine shells and frail tubeworms (*Ostrea* sp., *Chama* sp., *Serpula concharum* and *Pomatoceros lamarckii*), indicative of sheltered waters. The upper limit of this unit indicates the very close proximity of the shoreline. Contemporary sea level was therefore -1.64 m, with a precision of +/-20 cm. Marine shells fixed to the pebbles were dated at 4420 +/-45 years B.P.

A layer of free-living calcareous algae, whose upper limit is at -1.48 m NGF, overlies the pebbles. This bio-accumulation of the coralline Rhodophyte *Mesophyllum coralloide*s, a sublittoral species which may develop upwards to mean sea level in calm marine embayments, may be used as a sea-level indicator. Radiocarbon dating of thalli yielded an age of 3705 +/-45 years B.P. Contemporary sea level lay -1.48 m NGF with a precision of +/-20 cm.

The youngest marine sedimentary unit is a pebble beach characterized by a biodeposition of small branches, wood, and pine cones (*Pinus halepensis*). The upper limit of this stratum is at –0.9 m NGF, and thus it may be used as a sea-level indicator. Radiocarbon dating yielded an age of 2700 +/-30 years B.P. Contemporary mean sea level was therefore –1.1 m NGF at 2700 +/-30 years B.P., with a precision of +/-10 cm.
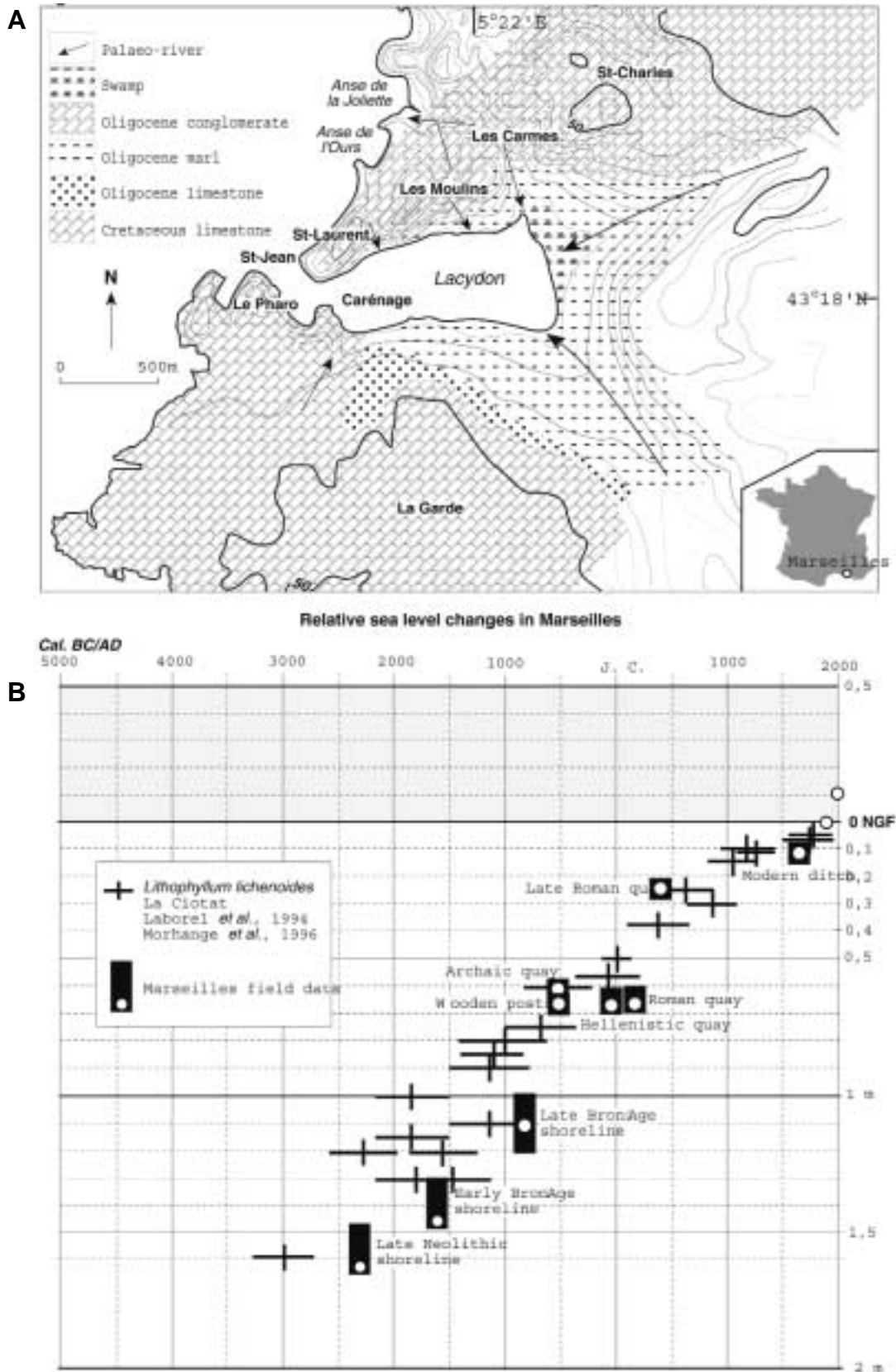
Fig. 1. **A.** Present time topographic and geological features of Lacydon creek (Marseille). Localization of the archaeological excavations. **B**. Age-depth diagram : data from Marseilles' archaelogical excavations compared with dated algal rims from rocky cliffs at La Ciotat (Laborel and Laborel-Deguen, 1994).

The surface of a Greek quay, built around 575 years B.C., was covered by fixed marine organisms. The upper limit of *Balanus* cf *amphitrite* is well preserved along more than 20 m, and marks a mean sea level at -0.63 m +/-5 cm NGF. The quay was silted up in 510-500 years B.C., the shells dieing-out due to sand from a nearby rivulet. The same sea level (-0.67 m +/-5 cm NGF at 510-500 years B.C.) was also observed on wooden posts.

A Hellenistic quay, built around 100 years B.C., was lined by wooden planks bearing scattered barnacles, with an upper limit of -0.68 m NGF +/-10cm. These died-out in 50 years B.C., when the quay silted-up and was abandoned. Contemporary sea level was therefore -0.68 m (+/-10 cm).

Wooden posts from a Roman quay (20 years A.D.) yielded scattered barnacles with an upper limit of -0.65 m NGF. The barnacles died-out around 150 years A.D. when the quay silted-over. Contemporary sea level was therefore -0.65 m (+/-10 cm).

Pirazzoli and Thommeret (1973) excavated a Roman quay built during the second part of the first century A.D. (Guéry, 1992). It bore a continuous line of barnacles (upper limit at -0.25 m NGF +/-5 cm), which died-out due to siltation around 450 years A.D. (Jourdan, 1976). Sea level stood at -0.25 m (+/-5 cm).

A medieval wall, connected to the sea, bore a continuous and straight upper limit of barnacles at -0.12 m NGF +/-5 cm. The barnacles died when the ditch silted-up in 1660 years A.D. Contemporary sea level was therefore -0.12 m, with a precision of +/-5 cm.

Discussion

Data obtained in Marseilles fit well with those from rocky-coast indicators such as *Lithophyllum* rims (Fig. 1, Laborel and Laborel-Deguen, 1994). The age-depth diagram shows a regular rise in relative sea level up to about 500 years A.D. followed by a period of stability. Total rise has been less than 1.5 m in the last 4,400 years. The rate of mean sea level rise was 0.4 mm/year between 4,400 years B.P. and 450 years A.D., and 0.2 mm/year since. Later, the rate of sea-level rise increased to around 1.5 mm/year during the 10th century A.D. (Blanc and Faure, 1990).

In Southern France, there is no evidence for any sea-level oscillation over the last 5,000 years (Aloisi *et al.*, 1978), except for the tectonically active region of Nice. Field observations for the Holocene do not show any levels higher than present. This is proven by the preservation, just above present sea level, of horses painted on a wall of the Palaeolithic Cosquer cave near Marseilles (Collina-Girard, this volume). Only the lower part of the painting has been blotted out by the sea, whilst any positive level oscillation would have also destroyed the upper part of the painting.

POST-ROMAN RELATIVE SEA-LEVEL MOVEMENTS IN POZZUOLI, PHLAEGREAN FIELDS, ITALY

History and methods

The region of Pozzuoli (Phlaegrean Fields, near Naples) is a volcanic complex. A third of the area presently lies below sea level, forming Pozzuoli bay. The caldera forming event, which occurred around 35,000 years B.P., produced the Campanian ignimbrite. A smaller eruption, 12,000 years B.P., produced ca. 10 km^3 of Neapolitan yellow tuff (Barberi *et al.*, 1991 ; Orsi *et al.*, 1998).

The absence of available data for the interval between the beginning of the Christian period and the 16th century is generally taken for granted. In 1538 A.D., an eruption formed the Monte Nuovo volcano. It was preceded by around 50 years of local ground elevation, culminating in an intense uplift crisis prior to the eruption (Dvorak and Mastrolorenzo, 1991).

Over the last two centuries, many scientists have been puzzled by the subject of relative sea-level changes in Pozzuoli. The columns in the Roman market are even pictured on the frontispiece of the famous *Principles of Geology* by Lyell. Lyell observed that many marine shells were found inside perforations on the marble columns. The work of Parascandola (1947) is the first modern synthesis. Dvorak and Mastrolorenzo (1991), Ager (1989), Gould (2000) and

Pappalardo and Russo (2000) deplore the lack of shells, taken away by tourists during the 19th century.

Scientific studies have recently been advanced by the two great brA.D.yseismic crises of 1969-1972 and 1982-1984 (Civetta *et al.*, 1995). However, no recent observations have been made of the biological remains still present on the Roman monuments and adjacent cliffs, with the exception of Giudicepetro (1993). It seemed that new field survey and additional datings could provide a complementary approach to this geodynamic issue. Marine fauna was collected *in situ* from different types of substrata and was analysed to establish the ecology of living species. Specimens were taken *in situ* and were in excellent condition.

Biological analysis

New observations were made at three different sites in Pozzuoli (Fig. 2): the columns of the Roman market, marine cliffs in the nearby district of Rione Terra, and excavations of a Roman structure (house 23 of block 23), also in Rione Terra (Crimaco and Giallanella, 2002). The first results have been published in two preliminary publications (Morhange *et al.*, 1999 and 2003).

Three sets of radiocarbon dates can be identified (Fig. 2).

• A first group is composed of recent dates. Along Rione Terra cliff, a branch of *Astroides caly- cularis* (at + 7 m) is dated 1245 years B.P., similar to the conventional date obtained on a near- by colony (1110 years B.P.). In the same marine cave, an oyster (at + 7 m) was dated 1225 years B.P.. In the Roman market, a lithophaga shell yielded a date of 1235 years B.P. The mean date for this first group is 1205 ± 20 B.P., or between the end of the 12th century and the beginning of the 13th century A.D. This chronological range represents the beginning of a structural emer- sion phase. A discrepancy of two centuries is explained by precise historical data showing an uplift of the substratum a few decA.D.es prior to the eruption of Monte Nuovo, in 1538. This stage of historical pre-eruptive uplift began at the end of the 15th century, as shown by two royal acts, released in 1503 and 1511, that distribute new, recently emerged littoral lands below Rione Terra. Around 1450 A.D, an illustration from the Codex of Edinburgh shows the two columns of the Roman market still in the sea, proving that uplift had probably not yet started (Giamminelli, 1996). Dvorak and Mastrolorenzo (1991) quote ancient texts establishing a local submersion of the Pozzuoli area around 1440 A.D. The radiocarbon dates appear to overestimate the historical data by about 200 years.

• The second set is composed of slightly older dates. Valves of *Chama gryphoides* were dated at 1735 years B.P. (600-750 years A.D). They settled on a Roman wall of Nero age, bearing a Roman cave of Rione Terra. This date confirms the high relative sea level already obtained on lithophaga shells from the columns in the Roman market (1875 B.P.). Another lithophaga shell, at around + 7 m, is dated 1955 B.P.. Thus, the mean age of this group is 1860 ± 25 B.P., or between the 6th century and the middle of the 7th century A.D. An initial phase of substratum uplift explains the death of the marine organisms. This mean radiocarbon date must be compared to the high precision archaeological date obtained on the bedded sandy marine deposit, which infilled a Roman cave from the excavation of Rione Terra, a few decimetres below the level of the *Chama* (Morhange *et al.*, 1999). Emersion of the beach is dated to the 9th century A.D. Here also, it seems that radiocarbon dates are about 200 years older than the historical dates.

• The third group comprises three dates. *A lithophaga* shell deriving from the market is dated 2185 years B.P.; another yielded an age of 2250 B.P. Conversely, still around + 7 m, two Vermets shells, removed from the same *lithophaga* hole, yield an age of 2225 B.P. The mean age of this last group is thus 2230 ± 25 years B.P. These radiocarbon datings are not compatible with the archeological and epigraphic data which show the Roman market functioned at least until the 6th century A.D. Seeing as the last mentioned date for this monument was 394 A.D., the radiocarbon dates appear to be overestimating by at least several centuries.

Discussion

Relative sea-level curves drawn by different authors (Fig. 2) suggest different scenarios for ground deformations since Roman times. From a biological perspective, it is obvious that a high sea level with small oscillations occurred, between the 5th and the mid-15th century A.D.
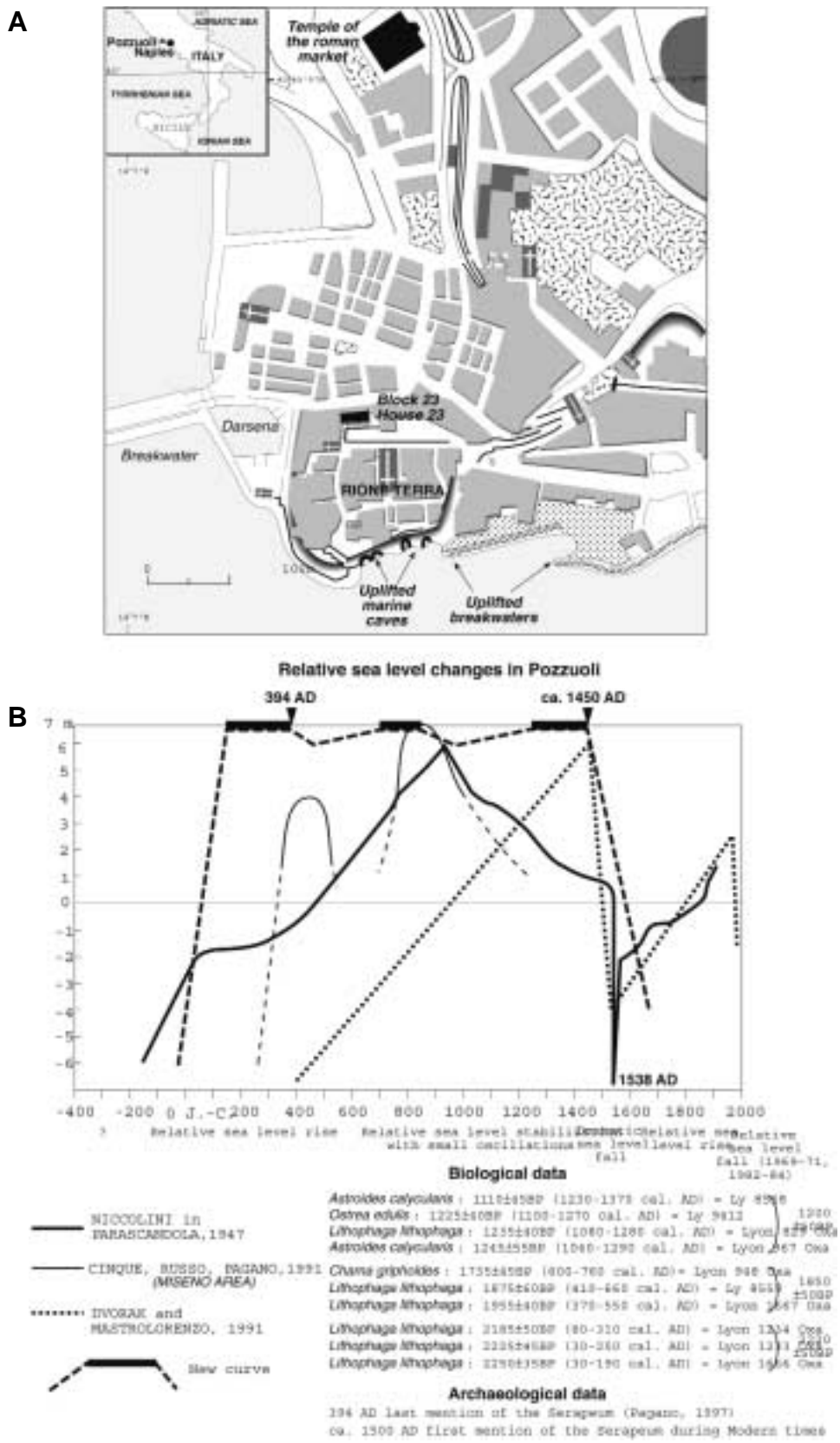
Fig. 2. **A**. Localization of the studied sites, Pozzuoli, Campania, Southern Italy. Tectonic diagram from Dvorak and Mastrolorenzo, 1991. The caldera boundary is defined on land by a series of scarps and at sea by shallow banks, probably submerged eruptive centers.
B. Age-depth diagram : relative sea level changes in Pozzuoli since 2,500 years.

Submersion was not a unique event, but comprised at least three oscillations. There was not only a short pick of submersion, as Parascandola (1947) and Dvorak and Mastrolorenzo (1991) asserted. Unlike previous thinking, these results do not reveal two different high sea levels since the Roman age, (Morhange *et al.*, 1999) but a fluctuating phase of high sea level that does not remain stable around + 7 m. Since Antiquity three positive sea-level oscillations can be distinguished :

• *Late Roman submersion* ending around 400 years A.D., and for which the duration of submersion can be estimated. When a virgin substratum is submerged, *Lithophaga* shells cannot settle on it for a few years, the shells reaching their maximum size at an age of about 70-80 years. Since the holes in the columns are quite large, it is feasible that the submersion lasted at least one century. Absence of a developed erosion notch in the column above the perforations suggests, on the contrary, that the period of submersion was not very long. This would temporally constrain the sea level rise to the 3rd century A.D., just after restoration of the Roman market (Parascandola, 1947). In the vicinity (the Cantieri Nautici Sud excavation), a first relative sea-level rise is documented at the end of the first century A.D. (Crimaco and Gialanella, 2003).

• *An Early Middle Age submersion* ended around 700-850 years A.D. As for the first event, the duration of this submersion is not precisely known.

• *A Late Middle Age submersion* ended around 1450 A.D. This period was followed by a well documented period of uplift, culminating in the eruption of Monte Nuovo in 1538.

We therefore propose that three separate periods of bradyseismic submersion occurred in Pozzuoli during historical times (Morhange *et al.*, 2003). The two recent crises of 1969-72 and 1982-1984 bear testimony to the fact that repetitive submersion events are relatively common in this area.

We thank J. Laborel and N. Petit Maire for helpfull suggestions.

Impact of geological processes and hazards on the Aegean civilisations in prehistorical and ancient time

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The Aegean region is known to be a site where geological and geodynamic processes are very active and evolve rapidly. It is also known that the time scale of most geological processes exceeds by ten to thousand and even million times man's life time. Nevertheless, the Aegean region is a place of continuous habitation during the last 35,000 yr, since the Paleolithic times, or even earlier.

Archaeological evidence and findings, ancient scripts from historical times and even myths of the Greek Mythology, provide, directly or indirectly, valuable information on the evolution of some of the geo-processes, as well as on the occurrence of catastrophic events and phenomena in the Antiquity and their impact on ancient civilizations. It is very common for geologists, working in the area, to relay upon ancient sources to verify or compare geological and geo-morphological data.

Thus, important maritime cities of the Antiquity were abandoned due to the seaward growing of the land in delta progradation areas or because of tectonically driven subsidence/uplift of the coastline. Others were totally or several times partially destroyed by earthquakes or tsunamis. Even the impact of the Holocene sea level rise may have been preserved as oral tradition between the successive prehistoric human generations and transformed into a myth in historical times.

The aim of this paper is to highlight and geologically explain some of the most typical cases of geo-processes, which affected in some way the development of ancient civilizations and to express the usefulness of the archaeological sources in the study of the Holocene Geology and vice versa. All localities mentioned in the text are shown in Fig. 1.

THE HOLOCENE SEA LEVEL RISE IN THE GREEK MYTHOLOGY

Two myths of the Greek Mythology may be related to the Holocene sea level rise. The first one is the Defkalion's flood, which may well be considered as a myth closely related to the Noah's flood, described in the Bible (see Lericollais *et al.* this volume). The second one is the Argonaut's expedition of Iason in the Black Sea and the pass through the Bosphorus strait.

Defkalion's flood: flooding of isolated basins, i.e. Gulf of Corinth

According to the myth of Defkalion's flood, Zeus was very angry because of the impiety and violent behavior of the people and decided to extinguish them by causing an enormous flood. Prometheus warned Defkalion and his wife Pyrra on the coming flood, and they constructed an Ark. During nine days and nine nights it was continuously raining, and the greatest part of the
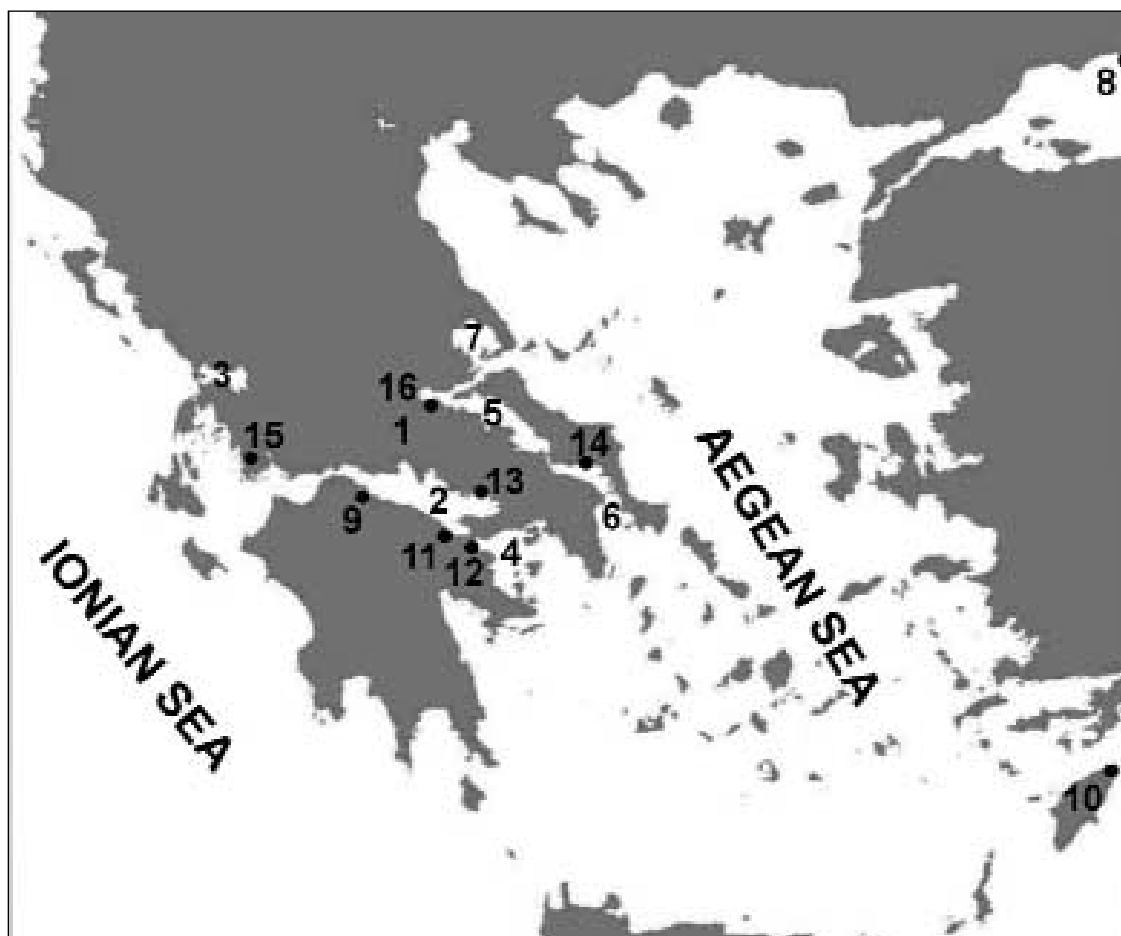
Fig. 1. Location map of the sites mentioned in the text. 1: Parnass Mt., 2: Gulf of Corinth, 3: Amvrakikos Gulf, 4: Saronic Gulf, 5: N. Evia Gulf, 6:S. Evia Gulf, 7: Pagasitikos Gulf, 8: Simpligadhes Petres / Bosphorus Strait, 9: Helike, 10: Rhodes island, 11: Lechaion, 12: Kechries, 13: Tifa, 14: Eretria, 15: Oiniadhes, 16: Thermopylae.

Hellenic region was flooded. Very few people survived the flood. Defkalion's Ark ("vessel") "docked" on the top of Parnass Mountain in Central Greece after the regression of the water. When did that happened?

It is known that the global Holocene rise of the sea level by 110-120 m started about 18,000 yr BP and proceeded at rates of 5-9 mm/yr. Higher rates of the sea level rise (25-37 mm/yr) may have occurred only during two short periods around 14,5 kyr and 11 kyr respectively (Bard *et al.* 1990). Nevertheless the above rates seem to be relatively slow in respect to the human lifetime. The available chronological data are very sporadic and do not allow a relatively precise definition of intermediate sea-level positions between the latest low-stand and the present high-stand in the Aegean region.

New data were obtained recently from the Gulf of Corinth where long piston coring in the basin of the Gulf of Corinth succeeded in penetrating the lacustrine sediments below the marine Holocene deposits at about 13-14 mbsf. AMS dating yielded ages of about 13,2 kyr BP for the establishment of marine conditions in the Gulf of Corinth (Lykousis *et al.*, in press). This age represents roughly the time that the Ionian Sea overflowed the Rion-Antirrion strait (62 m present day depth) and flew into the Gulf of Corinth lake.

High-resolution seismic data from the northern margin of the Gulf revealed the presence of continuously subsiding prodelta prograding sequences. The subsidence rate was estimated to 1 mm/yr. The topset-foreset transition of the last glacial prodelta deposits lies at about 105 m below the present sea-level (Fig. 2). Considering the subsidence rate and the relative position of the topset-foreset transition in respect to the water level we may conclude that: i) the water level
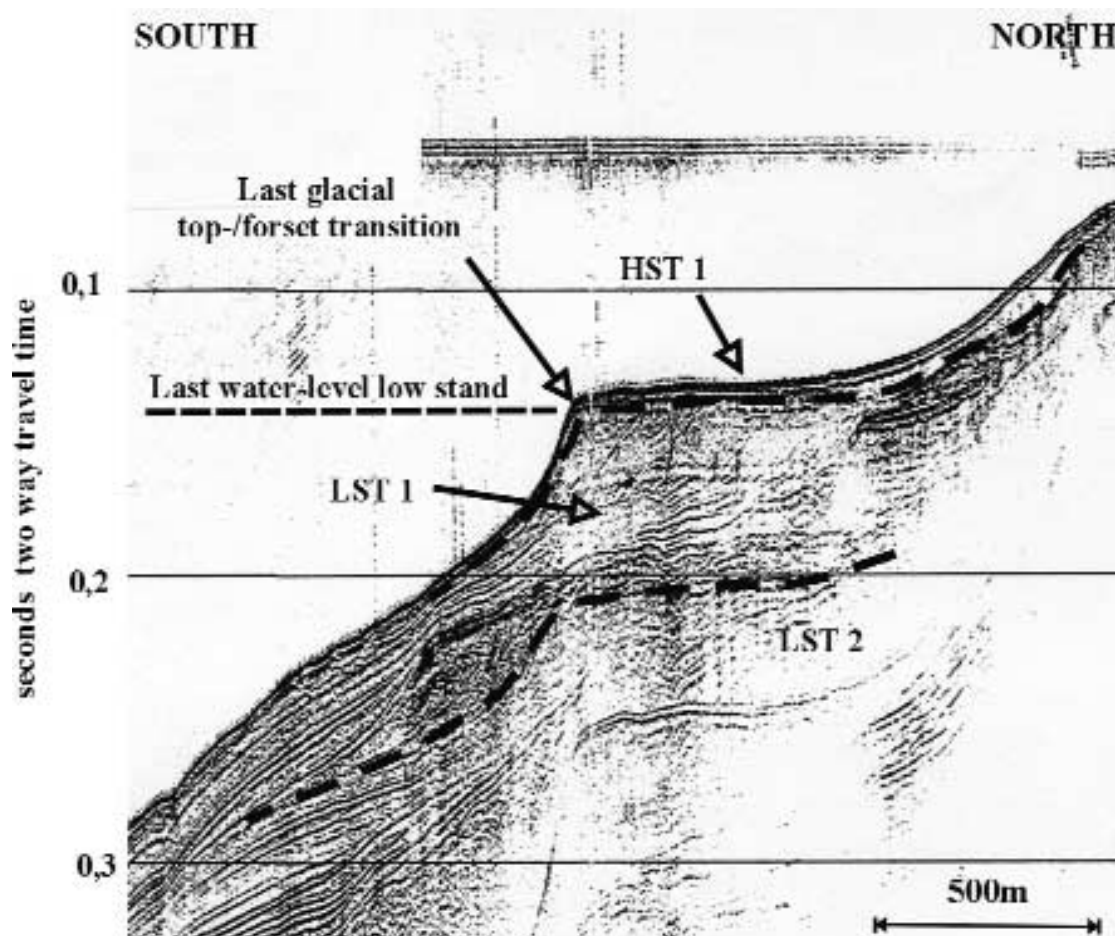
Fig. 2. Air gun single channel profile, Gulf of Corinth northern margin. The topset-foreset transition of the prodelta deposits (LST 1) of the last glacial maximum indicates the position of the water level in the Gulf at least 85 m below present sea level. HST 1: Holocene high system tracks; LST1: Last glacial low-stand system tracks. Oiniadhes, 16: Thermopylae.

in the Gulf of Corinth during the last glacial maximum was at least 85 m below the present sea level and ii) the Gulf of Corinth was a lake isolated from the open sea, with a lake level some 20-25m below the Rio-Antirio strait.

Single channel profiling in the area to the east of Rio-Antirio strait showed the existence of an erosional channel on the sea floor of the western Gulf of Corinth (Fig. 3). We interpret this channel as the result of the inflowing sea-water when entering into the former Corinth lake from the west. If this assumption is true, then the rise of the water level in the former Corinth lake from -85 to -60 m must have been very rapid and very impressive for the Paleolithic habitants of the surrounding lowlands. After that, and leaving out of consideration the local tectonic vertical movements, the rise of the water level should have slowed down, following the global sea level rise.

The same phenomenon must have taken place in all Gulfs, which are connected with the open sea (Aegean or Ionian) through shallow straits, like Amvrakikos Gulf, Western Saronic Gulf, Northern and Southern Evia Gulf, Pagasitikos Gulf, etc. The timing of the very rapid water level rise in each Gulf / former lake depends on the depth of each strait. It is thus quite possible, that the myth of Defkalion's flood roots on the initially very rapid rise of the water level of former, last glacial lakes which became marine Gulfs.

Argonaut expedition

One of the adventures that the crew of Argo had to overcome during the Argonaut expedition from Iolkos, in the Pagasitikos Gulf, to Colchis, in the Black Sea, was the pass through the Simpligadhes Petres. The Simpligadhes Petres used to be two huge rocky cliffs, located just
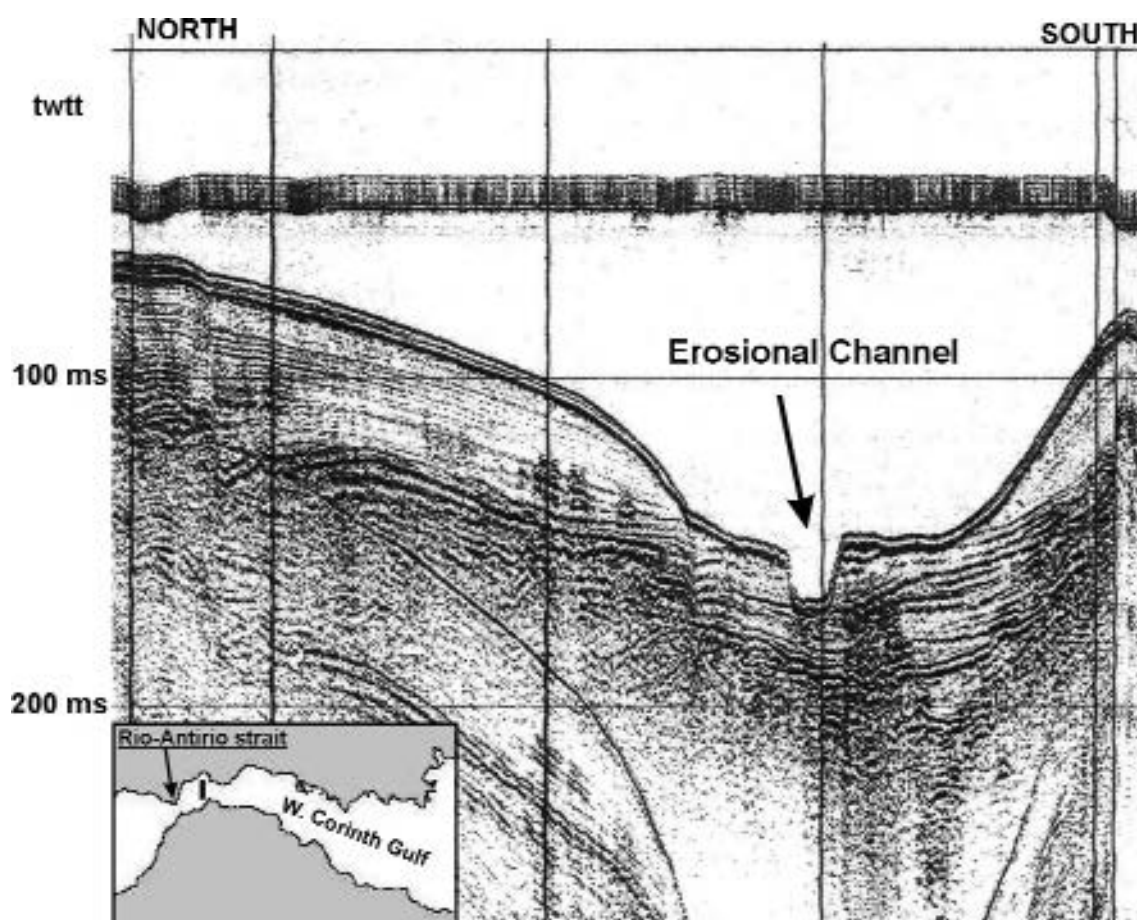
Fig. 3. Air gun single channel profile across the Gulf of Corinth showing the presence of the erosional channel east of Rio-Antirio strait.

before the entrance in the Black Sea. According to the myth, they were successively closing and opening. The soothsayer Phineas advised Iason to let a pigeon fly first through the rocks and if it would succeed, then they would succeed too. So it happened and Argo passed through the Simpligadhes Petres with minor damages at her stern. After that the Simpligadhes Petres remained open forever.

The retrogressive movement of the closing cliffs may refer to the relative rise of the water level in the Aegean Sea, the Sea of Marmara and the Black Sea, and the timing of overflowing the Bosphorus Strait, which is still debated (see Lericollais *et al.*, this volume).

EARTHQUAKE DISASTERS IN ANTIQUITY

Egeladhos was one of the Giants who took part in the fight against the Olympian Gods. Athena, who raised up from the head of Zeus, defeated him, let him fall down and then she threw the island of Sicily island upon him. Any time Egeladhos is moving, the earth is shaking and an earthquake happens. This is the way earthquakes are being explained in Greek Mythology. Earthquakes seriously affected most of the known civilization centers of the Greek Antiquity.

The devastation of ancient Helike (373 B.C.)

The soundest case is the devastation and sudden subsidence of Ancient Helike, the metropolis of the Ionic and Achaic Dodekapolis. It was located in the alluvial plain of Aigialia by the southern coast of the Gulf of Corinth. According to Pausanias and Strabo the ancient city was 7,2 km to the east of Aigion and 2,2 km from the coast, between the rivers Selinous and Kerynitis. A very strong earthquake completely destroyed the city in 373 B.C. The earthquake was followed by a tsunami, which drowned the ruins. The entire city and the surrounding lowland submerged

suddenly. Only the tops of the trees remained above the seawater level after the earthquake. The ruins of the city were visible on the seabed for many years after the earthquake and certainly until the second century AD, when Pausanias visited the area. Archaeological excavations, carried out on land during the past decades, have failed up to date to discover the ruins of the Ancient Helike.

Papazachos and Papazachos (1989) estimate magnitude Ms:7.0 for the earthquake of 373 BC, which devastated the ancient city. Such a strong earthquake may have caused extended liquefaction and subsequently subsidence of the alluvial plain. The strong seismic motion may have been triggered coastal sliding and failure as well as submarine landslides and the tsunami, which drowned the city. Fig. 4 shows the structure of the Gulf of Corinth basin off the delta plain of Aigialia, where the ancient city of Helike used to be. Extensive submarine sliding along the faulted slope of the basin is quite obvious.
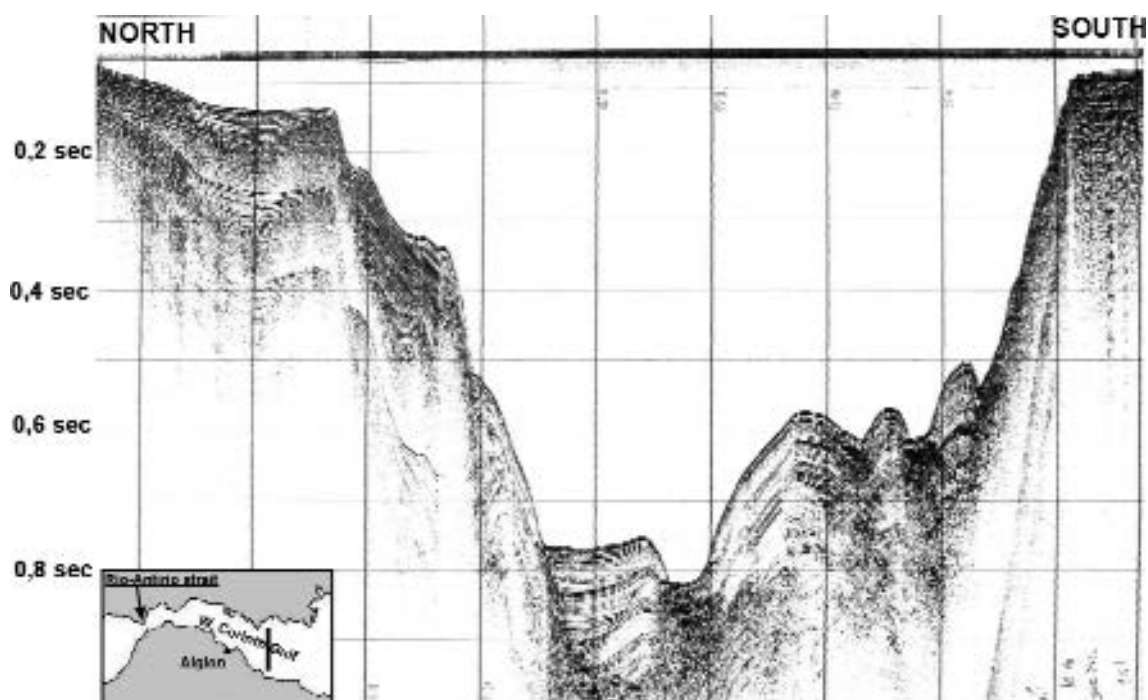
Fig. 4. Air gun single channel profile across the Gulf of Corinth showing extensive slumping off the assumed ancient Helike site.

Similar phenomena have occurred repeatedly since then in this area. Recently, the Ms: 6,5 Aigion earthquake in 1995 caused coastal sliding along several kilometers of the coastline and was followed six months later by a 2 m high tsunami. A 5 m high tsunami, the highest ever observed, hit the area after the 1817 earthquake (Papazachos and Papazachos, 1989). In 1873, December 26th, a Ms: 6.7 earthquake caused extensive liquefaction, while a 100-200 m wide coastal land stripe collapsed seaward, between Aigion and Diakofto. Schmidt (1875) reports that the vertical throw produced on the Helike fault was about 1 m. It is quite possible that Helike fault moved also during the 373 BC earthquake, although this is not proven yet.

Nevertheless, all known earthquakes recorded in the area since then caused phenomena, which are much weaker than the ones produced by the 373 B.C. earthquake. If the descriptions of Pausanias are precise, then the sudden submergence of Ancient Helike, which prior to the earthquake was 2.2 km away from the coastline, below the sea level, requires quite impressive subsidence of the alluvial plain, liquefaction and coastal failure (Lykousis *et al.*, 1997). Detailed geological mapping, high-resolution geophysical inspection and verification by drilling and radio-chronology, both on land and offshore, are needed to investigate the region. Since the ruins of the ancient city are still missing, the geological-geophysical survey will contribute significantly to the tectono-sedimentary and geomorphologic evolution of the alluvial-deltaic plain of Aigialia and to the search for Ancient Helike.

The demolition of the Colossus of Rhodes (227 B.C.)

The island of Rhodes has suffered strong earthquakes in recent times as well as in Antiquity. The 30 m high statue of the Sun, the famous Colossus of Rhodes, one of the seven wonders of Antiquity, was destroyed by an earthquake in 227 B.C. Pirazzoli *et al.* (1989) suggest that the earthquake, which destroyed Colossus, was also responsible for the sudden uplift of the coastline by 3.8 m.

VERTICAL TECTONICS

Vertical tectonics has affected most of the known coastal centers of the ancient world. Flemming *et al.* (1971) list over seventy coastal archaeological sites around the Peloponese and along the Turkish Aegean coastline which are vertically displaced by +3 m to –5 m relative to the present sea level. All along the coastline of the Aegean and Ionian Seas as well as in the Gulfs and on the islands one can find submerged or uplifted ruins of historic or prehistoric settlements. These vertical changes are local phenomena and cannot be simply interpreted with global sea level rise. Local tectonics and fault movements have to be carefully investigated site by site, to explain the vertical movements of the land relative to the sea level. A detailed listing of the known ancient coastal installations, initially located at the sea level, and indication of their present position relatively to the sea level would be a very important first step towards this direction, providing valuable information on the local vertical tectonics of the Aegean region.

A few examples are listed below to highlight the effect of vertical tectonics on the evolution of the ancient civilization centers.

Ancient Corinth: Lechaion vs. Kechries harbors

Ancient Corinth is reported to maintain two harbors on both sides of Isthmus. Lechaion was the one in the Gulf of Corinth, while Kechries was the harbor in the Saronic Gulf. The harbor installations of Lechaion were established in the 6th century B.C. and the port became very important during the 4th century B.C. at a time when Kechries used to be very important for the communication of the Corinthians to the east. The destiny of both ancient harbors was somehow different. Lechaion harborhas been silted up by sand and silt and is uplifted by several tens of centimeters. On the contrary the harbor installations of Kechries are now located about 1 m below sea level, obviously due to vertical tectonics.

Ancient Tifa

The northern margin of the Gulf of Corinth has undergone continuous subsidence during the last 250 kyr (Lykousis *et al.*, in press). The ancient city Tifa is located in the Gulf of Domvrena, a narrow gulf at the northern margin of Alkyonides Gulf, and is mentioned in the Argonaut Expedition. Tifys, who was coming from the city, was chosen to be the captain of Argo. The present location of the ruins of buildings and harbor installations below the sea level verifies the geologically observed subsidence of the area.

Ancient Eretria

Similarly to Ancient Tifa, a large part of the ancient city of Eretria, at the eastern coast of the Southern Evia Gulf now lies below the sea level. Kabouroglou (1989) suggests that 'the sea level around Eretria has risen by at least 2 m since the 8th century BC'.

ANCIENT HARBORS AND DELTA PROGRADATION

Alluvial plains developed at the river deltas are common places for human settlements throughout history. At the same time, deltaic plains are sites of rapid seaward progradation of the land. Many important maritime cities of the Antiquity, settled initially on the coastline, were after some time abandoned, because of the rapid accumulation of the delta deposits.

Ancient Oiniades

The ancient city of Oiniadhes was settled before the 5th century B.C. on a hill in the Aheloos delta plain. Oiniadhes became a significant port of western Greece and took part in the Peloponesian War in the 5th century B.C. Impressive ancient shipyard installations at the foot of the hill indicate that the city was an important maritime center in the Ionian Sea. The city was

abandoned in the 1st century B.C. or slightly later. The present location of the ancient shipyard is within the delta plain of Aheloos river, about 5 km away from the sea.

An excellent description of the Ahellos delta plain as well as reconstruction of the delta progradation is provided by Vött *et al.* (this volume), based on drilling, paleo-environmental analyses and radio-chronology.

The Battle of Thermopylae (480 B.C.)

The Battle of Thermopylae in 480 B.C. is an example of exceptional bravery and self-sacrifice of Leonidas and his 300 soldiers from Sparta together with 700 soldiers from Thespies, who fought against 2 million soldiers of the Persian army under the leadership of Xerxis. In 480 B.C. Thermopylae used to be a narrow land stripe between the steep mountain slopes and the sea. The width of this land stripe was about 800 m and thus, it could be blocked by the 1000 Hellenic soldiers. In the 2,500 years following the Battle of Thermopylae, the narrow land stripe grew rapidly and is today 5 km wide. The area of Thermopylae is located on the southern shore of Maliakos Gulf, in the delta system of Sperchios river.

Landscape changes due to earthquakes and tectonic uplift in the Iberian Peninsula littoral during the last 20,000 years.

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INTRODUCTION: LANDSCAPE CHANGE AND ACTIVE TECTONICS

The concept of seismic landscape concerns the geomorphological structure of active cordilleras and/or range-front faults built by successive earthquakes during the Quaternary period. These Quaternary events can be archived within the geological record (i.e. seismites), but abrupt landscape changes triggered by tectonic activity during the last 20,000 years can be also preserved in the geomorphological record. For more recent time-scales (i.e. last 8,000-9,0000 years) large earthquakes commonly interfered with human activity and are incorporated into the archaeological and/or historical records. Therefore, to relate tectonic impact to the environmental history of ancient populated areas, human archives and geo-archives must be analysed, evaluated and compared. Aside from historical references, the most common human record of large earthquakes is the generation of horizons of destruction (and/or demolition) among the different archaeological layers of ancient cities. However, in spite of the conspicuous interferences of large seismic events with human activities in the Mediterranean, permanent landscape changes linked to active tectonics are extremely rare.

Recent revisions of Earthquake Intensity scales based on geological and geomorphological evidence (Serva, 1994; Michetti *et al.*, 2003) indicate that ground changes become significant from Intensities up to VIII MSK, and only print relevant permanent traces in the landscape from Intensity X MSK. On the contrary, relevant earthquakes, but of smaller intensities (VI-VIII MSK), have a minor environmental impact and coseismic landscape change is minor, temporary and hardly ever preserved in the geomorphogical record. Environmental changes produced by strong seismic events can be of induced and/or primary (sesmogenic) character.

*Primary coseismic effect*s (i.e., surface faulting) may dislocate the ground surface from ca. 0.5-2.0 m (X MSK) to several meters (XI MSK) or tens of meters (XII MSK) over rupture

lengths ranging from several tens (X MSK) to several hundred kilometres (XII MSK). These are normally associated with tectonic subsidence or uplift of the ground surface of the order of numerous meters over areas of hundreds km^2. In extreme cases, geomorphological changes can attain extraordinary extent (> 1,000 km^2) and size. The typical cases are the abrupt uplift or subsidence (inundation) of coastlines by several meters (i.e., Ms 8.6 AD 1964 Alaska event) river change or avulsion, development of waterfalls and formation or disappearance of lakes (Michetti *et al.*, 2003).

Induced coseismic effects can be even more significant; they include rock-falls, landsliding, karst vault collapses, large open fractures, and in particular cases (offshore dip-slip faulting) tsunamis. Other environmental changes, such as aquifer changes and soil liquefaction can be relevant but the impact on the landscape is normally minor or temporary. Landslides are the more prominent processes in inland areas, and may reach very large size of 10^5 to 10^6 m^3 over surface areas of hundreds to thousand of km^2, even at 200 – 300 km distance of the epicentre for events up to X MSK (Keefer, 1984; Rodriguez *et al.*, 1999). In particular cases, landslides may dam narrow valleys, causing temporary or even permanent lakes and/or affect to entire valley slopes generating many barrier lakes. Tsunamis, and the formation of large waves in still and/or running waters (seiches), have a high potential of destruction over littoral zones (i.e., AD 365 Creta event; AD 1755 Lisbon Tsunami). Their potential of preservation in the geological record is high, but poor in the geomorphological one, except in the case of "very extreme" events. Tsunami run-up and swash can give place to the rupture of spit –bars and inland deposition of sand-gravel sheets forming washover fans of variable texture and size. In contrast, the backwash is usually associated with erosion process that can give place to dramatic changes in the backshore drainage (Dawson, 1994). Whatever the case, tsunamis are not an exclusive product of offshore seismic events; other processes such as volcanic explosions and submarine landslides can also trigger these processes.

In spite of the effect in the landscape caused by strong earthquakes they almost have a fatal impact on population and buildings within the epicentral zones. Additionally, secondary effects such as "fires" and rupture of artificial hydrological elements (i.e., earth-dams, levees, etc.) can devastate large populated areas causing many injuries, but the damage radius is normally smaller than 100 km, and exceptionally over a few hundred of kilometres (i.e, 1985 Mexico Earthquake). Obviously, damage increases with the Intensity of the earthquake. But, increasing damage (i.e. degree of city destruction) does not essentially equate with the extent and size of the environmental permanent change printed in the landscape. Other slower processes working on larger time-scales (i.e. surface uplift and/or subsidence) can be, on the contrary, more effective as landscape changers. These processes can instigate dramatic geomorphological (and environmental) adjustments when they interfere with the fluvial system affecting the available fresh water resources of large areas. Sometimes seismic events, not necessarily strong, act as trigger processes when uplift-subsidence move the fluvial system to conditions close to non-equilibrium and/or disequilibrium.

HISTORIC AND PREHISTORIC EARTHQUAKES

In the Mediterranean waterfront of the Iberian Peninsula, Quaternary deformations and recent paleoseismic features are closely related with the activity of low slip-rate faults. This is the case of the Betic Cordillera and Catalan Coastal Ranges, where faulted mountain fronts are the more conspicuous large-scale landforms generated by Quaternary tectonics. Uplift rates obtained from the analysis of Late Pleistocene raised beaches (Zazo *et al.*, 1999a, 2002) and range front faults (Silva *et al.*, 2003) vary between 0.1 mm/yr and 0.02 mm/yr, diminishing from South (Gibraltar Strait) to North (Catalan Coastal Ranges), showing a similar behaviour in the Balearic Islands. Vertical slip rates directly estimated for recent faulting events (< 18 kyr BP) within the Betic Cordillera are of 0.10-0.20 mm/yr, but linked to strike slip-rates of 0.15-0.32 mm/yr (Masana *et al.*, in press). On the contrary, again in the North coast slip rates related to faulting events are slower, and never gone up to 0.02 mm/yr (Masana *et al.*, 2001). However the entire littoral area displays a low to moderate instrumental seismicity, but has been affected by significant (catastrophic) historical earthquakes.

At least twelve strong *historic earthquakes* (≥ IX MSK) have struck the Iberian littoral during the last 2,000 years. Aside the Baelo Claudia case-events (40-60 AD and 350-395 AD), which are only archaeologically evidenced (Menanteau *et al.*, 1983; Sillères, 1997; Silva *et al.*, in press), the other strong events are historically documented. They concentrate between 1300 AD to 1900 AD (Table 1) and show a broad frequency of one event per 100-150 years with an estimated magnitude of Ms 6.0-7.0. However recent revisions of the historical seismicity during the Spanish Arab Period (711-1429 AD) indicate the occurrence of strong events within Al-Andalus during the years 881, 957, 1024-1025, 1079-1080, 1169-1170 and 1406 AD (Espinar Moreno, 1994).

Table 1. Strong seismic events occurred in the Iberian Peninsula and their reported effects on landscape and population. (NC): Non-Catalogued seismic events

Year (AD)	Epicentral locality	MSK Intensity	(Ms) Magnitude	Damage	Landscape and environmental change
40-60 (NC)	Baelo Claudia (Bolonia / Cádiz)	≥ IX		Private and public buildings destroyed and/or demolished. Destruction of Basilica and Macellum, and City walls. Widespread pop-up like structures in the pavement.	Landslides on artificial banks and liquefaction processes (site effect)
350-395 (NC)	Baelo Claudia (Bolonia / Cádiz)	≥ IX		Destruction of Basilica and Macellum, and City walls. Widespread pop-up like structures in the pavement.	Landslides on artificial banks and liquefaction processes (site effect)
1048-049 (NC)	Ancient Tudmir (Murcia)	VIII - IX		Destruction of buildings and many injuries	Large open cracks, many springs dried and widespread liquefaction with gas- emissions
1396	Tavernes (Valencia)	IX- X		Collapse of towers and bridges. Hundreds of houses destroyed	Rockfalls, open fissures in the ground and liquefaction processes (site effect)
1428	Queralps (Girona)	IX		800 deaths/ Churches and tower castles seriously damaged. Many houses damaged	Open fissures in the ground
1431	Atarfe (Granada)	IX		Damage in towers and mosques. Walls of the Arab Castle partially collapsed	
1504	Carmona (Sevilla)	IX		100 deaths/ destruction of city walls, collapse of roofs and damage in many houses.	Large landslide event on the mainland scarp of the city. Open fissures in the ground
1518	Vera (Almería)	IX – X		>80 deaths/ Complete city destruction.	Landslide event/events. City founded on pronounced slope (topographic effect).
1522	Almería city	IX		> 2,500 deaths/ Complete city destruction. Serious damage in another 80 different localities destruction. Harbour destroyed	Offshore event with relevant Tsunami
1680	Málaga city	IX	6.8 –7.0	200 deaths and 250 injuries / Destruction of the ancient Arab Castle. 852 houses destroyed and 1,250 ones damaged	
1748	Enguera (Valencia)	IX	6.2	Churches and tower seriously damaged. Many houses damaged	
1804	Dalías (Almería)	IX		150-200 deaths/ Collapse of churches and towers, several hundred of houses destroyed	
1829	Torrevieja (Alicante)	X	6.5 – 6.9	389 deaths and 388 injuries / About 2,900 houses destroyed and around 2,000 ones damaged.	Open fissures on the ground, Liquefaction and mud-volcanoes (site effect)
1884	Arenas del Rey (Granada)	IX-X	6.5 – 6.7	900 deaths and about 2,000 injuries / 1,000 houses destroyed and 17,000 damaged	Surface faulting, Large landslides, open fissures and localized liquefaction processes.

These data strongly suggest that seismic activity has periodically shaked the Mediterranean littoral since (at least) the early Roman period.

Between the strong events seismic activity is characterized by small-magnitude earthquakes (< 4.0 mb) punctuated by occasional moderate events (4.0-5.0 mb) as illustrated by current instrumental records. These moderate events are normally associated with intensities of VII-VIII MSK, which normally have minor impact on both landscape and population. Landscape changes corresponding to the strong historic events have been reported as normally minor (Table 1). Moderate landslides in unstable equilibrium slopes, and liquefaction processes in wet lowlands and/or marshlands (Table 1), are most common effects, in both cases highly conditioned by geological "site effects". Only in the case of the 1884 AD Arenas del Rey event, the last strong earthquake (IX MSK and Ms 6.5-6.7) felt in the Iberian Peninsula, was minor surface faulting produced (Reicherter, 2001), still a prominent visible feature (ca. 15 km length) in the landscape.

The Baelo *Claudia case* is related to apparent recurrent severe damage in this ancient Roman city located at the edge of the Gibraltar Strait during 40-60 AD and 350-395 AD (Table 2). In both periods the city underwent an entire process of destruction and/or demolition. In the first period the city was rebuilt, but the second one led to the abrupt decay and abandonment of the

Table 2. Periods, events and geological processes related to the configuration of the Archaeological site of Baelo Claudia. From Silva *et al.*, (in press)

DATES	HISTORICAL FEATURES	ARCHEOLOGICAL MILESTONES	GEOMORPHIC AND HUMAN PROCESSES
Before late 2nd Century BC	No urban settlement in the zone		Colluvial slopes partially bury staircase marine terraces. Dune system development (D_1) on the Holocene spit-bar system.
Late 2nd Century BC	**First Roman settlement**	First "Fish" Factories; increasing commercial activity with Africa.	Scarce human modification (or not documented). Local Incorporation of archaeological artefacts to surface formations
Late 2nd Century BC to Middle 1st Century AD	**First Building phase** (lower coastal sector). First settlement becomes *Oppidum latinun* (Category of Roman City). Major urban reforms.	Construction of Forum, Ancient Basilica, *Macellum* and City Walls (ca. AD 10-20). Urban orthogonal pattern.	Major landscape reworking. Ground digging; generation of artificial talus on colluvial slopes; Soil beheading and alteration of surface hydrology.
ca. AD 40-60 PROBABLE EARTHQUAKE	**Demolition** and/or collapse of private and public building. Damage of City Walls.	Demolition horizon overlays claye substratum, folded roman pavement and house foundations in the lower sector of the city	Ground levelling; Silty-clay artificial filling with incorporation of large architectural elements.
Late 1st Century AD to late 4th Century AD	**Second Building phase** Maximum extension and prosperity of the city, which acquires the imperial label of "*Claudia*" at ca. AD 48 -50.	Development of the Monumental zone (Basilica, Temples, *Forum*, *Curia*, and Theatre). Recycling of previous architectural elements, and partial use of former foundations.	Rebuilding of the city on the "demolition horizon", artificially cemented on surface.
Late 4th Century AD. (ca. AD 350-395 ?) PROBABLE EARTHQUAKE	**Abrupt ruin and urban depopulation.** The damaged city was never fully abandoned or rebuilt.	Pop-up like deformations in *Forum* and *Decumanus maximus*. Collapse of Basilica column drums and *Macellum* roofs. Westwards tilting of most walls and City Walls.	Roman and post-roman colluvial Formations bury the damaged remains of the city. Coastward shifting to Dune system D_2.
Late 4th Century AD to ca 7th Century AD.	**Third Building phase.** Small paleo-Christian settlement on former monumental zone, with different urban pattern.	Definitive abandonment before the AD 711 Arab conquest of the Iberian Peninsula	Colluvial burying of the destroyed roman city. Soil swelling and slope creeping.

city (Sillères, 1997). However these events have the particularity of not being referenced in historical documents and presumably were unnoticed in other close roman settlements. Only apparent archeoseismic evidence supports their occurrence (Menanteau *et al.*, 1983; Silva *et al.*, in press). The lower sector of the city founded on unstable ground constituted by artificial roman-soil fillings over expansive clayey substratum, displays abundant disrupted architectural relics. They include faulted or disrupted walls and pavements, tilted city-walls, and collapsed columns, strongly pointing to historic earthquake damage (Fig. 1). Other probable earthquake-related effects such as landsliding and liquefaction are documented, indicating the relevant role of ground destabilization and water-participation in city destruction. Among the main probable coseismic features, relevant landsliding affecting pavement and house walls belonging to different building periods is the unique documenting recurrent damage.
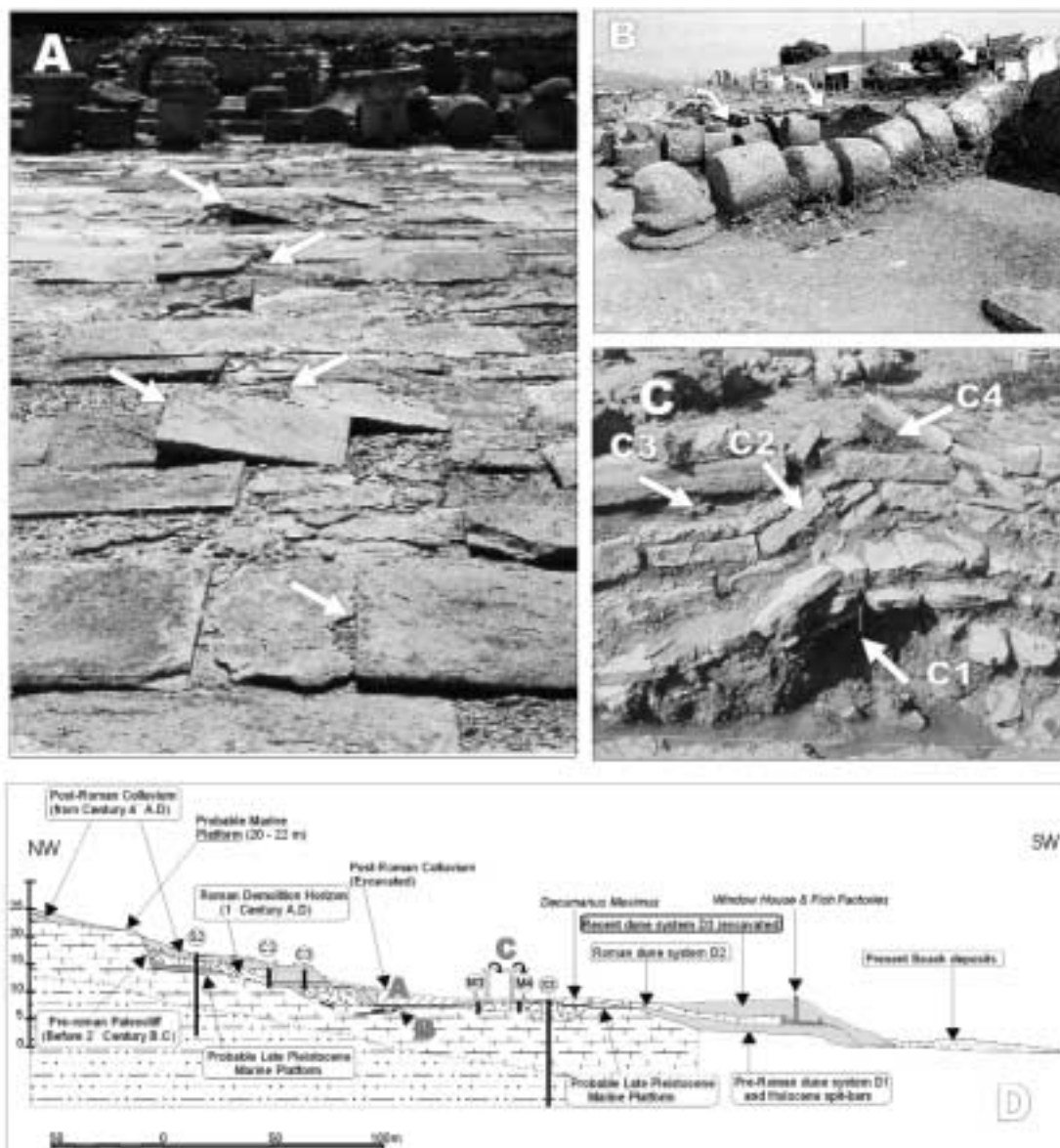
Fig. 1. Archeoseismic evidence at Baeolo Clauidia (Bolonia, Cádiz). (A) Pop-up like deformations of Flagstones in the Forum of Baelo Claudia. Arrows indicate overthrusted slabs. (B) Southerly collapsed columns at the Basilica (after Sillères, 1997); (C) landslide-induced folded and upthursted remains at the NW corner of the Forum. C1: Folded Roman pavement AD 40-60; C2: faulted house ashlars AD 40-60; C3:Demolition horizon AD 40-60; C4: upthrusted house-basement AD 350-395; (D) cross-section of the ancient urban area of Baelo Claudia inferred from well-log and trench data (A, B, and C locate photographs sites). Dotted lines represent the excavated zones.

The geological and geomorphlogical data suggest that moderate (ca. 5 mb) local seismicity on the offshore prolongation of close NE-SW active strike-slip faults can account better for the observed destruction than strong events far away (i.e. 365 AD Crete event) as initially proposed by Menanteau *et al.* (1983). Nevertheless, the more recent bias (Espinar Moreno, 1994) tend to consider the 365 event as having occurred in the Mediterranean littoral of Spain as initially proposed by Galbis (1932). In any case, the unstable character of the ground (site effect) and possible directivity effects have to be considered even in the case of the close event to explain the extent of destruction recorded in the city. Also in this case, coeval geomorphological changes are unnoticeable, and probably the significant economic decay of the sinking Roman Empire could play the major role in the eventual abandonment of the city. The reported ground deformations and archeological disturbance, conjugated with the city history (building periods), strongly indicate recurrent seismic damage as in other cases in the Mediterranean (e.g. Stiros and Papageourgiu, 2001; Altunel *et al.*, 2003; Altunel, this volume). However, the available data are not conclusive, and the earthquake problem of Baelo (dates, location, size and even occurrence) is still an open debate.

A particular case is constituted by the strong seismic events (Ms 8,5-9) produced in the Gulf of Cádiz – Azores area, which can be felt with high intensity (<IX-X) along the Atlantic coast of the Iberian Peninsula, accompanied by tsunami events. This was the case of the 1755 AD Lisbon Tsunami, which produced thousands of victims over the Gulf of Cádiz littoral and very severe damage in the coastal cities of Faro (Portugal), Huelva and Cádiz (Spain) among others. In spite of the severity of this event on population and buildings, its more prominent geological vestige in the Spanish coasts are four modest (< 300 m length) washover fans breaking the younger spit-bar unit (H4: 500 yr BP) of Valdelagrana in Cádiz (Luque *et al.*, 2001). Other older tsunami event has been recorded in the Gulf of Cádiz from different borehole records in the Valdelagrana spit-bar and the Doñana Marshlands. Its age (2,500 yr BP) matches with historical and archeological records of the zone and can be related to tsunamis events occurred in 218 and 216 BC (probably the same) listed in the Spanish Seismic Catalogue (Luque *et al.*, 2002). These events (or event) are also recorded as several degraded washover fans breaking the Holcene H3 unit (2,550-2,330 yr BP) of the Valdelagrana spit bar (Luque *et al.*, 2001). Therefore whasover fans are the more common geomorphological vestige of tsunami occurrence on the Spanish coast

*Paleoseismic studie*s carried out in Spain are still few. First results have highlighted the active nature of some fault zones in the Betic Cordillera and the Catalan Coastal Ranges. In Murcia some paleoseismic events have been generated by the Lorca-Alhama de Murcia Fault in 16.4 kyr BP and in ca 1460 AD (historical – not catalogued). The maximum magnitude obtained from the rupture area and from the slip per event measured at trenches is of Mw=7.0+/-0.1 (Masana *et al.*, in press), which exceeds the largest earthquake recorded in the Spanish Seismic Catalogue. In the Alicante region, the available information about recent paleoearthquakes comes from several seismite layers identified in core samples from the Late Pleistocene-Holocene lacustrine filling of the Lower Segura Basin (Fig. 1). Paleoseismic events broadly cluster in two periods of 2-4 kyr BP and 10-13 kyr BP, which can be considered as periods of enhanced seismic activity in the Murcia – Alicante area. The analysis of the more recent ones allowed to identify the occurrence of seven major events (Ms >6.5) during the last 8,000 years, with a minimum recurrence interval of ca. 1,000 years (Alfaro *et al.*, 2001). Lastly in the Catalan Coastal Ranges, the El Camp normal fault (near Tarragona) has been classified as active one with three paleoseismic events identified for the last 125,000 yr. On the basis of the different tectonic features observed in trenches, the recurrence period of large earthquakes during this time-period is estimated to be around 30 ka and the elapsed time since the most recent event, to be around 3000 years. Using the fault length and the vertical displacement per event, the largest estimated earthquake had a magnitude of Mw 6.7. In all cases, the signatures printed in the landscape by all the presently identified paleoseimic events occurred during the last 20,000 yr in the Iberian Peninsula remain uncertain, and/or maybe assembled in the present geomorphological arrangement of large range front-faults. However, it is necessary to consider that their estimated magnitudes (6,5-7,0) are commonly associated with modest displacement per event of 0.6-4.0 m (Michelli *et al.*, 2003).

Thus geological and human archives are complementary as they record different temporal scales. Only in their overlap zone data can be compared, evaluated and tested in order to under-
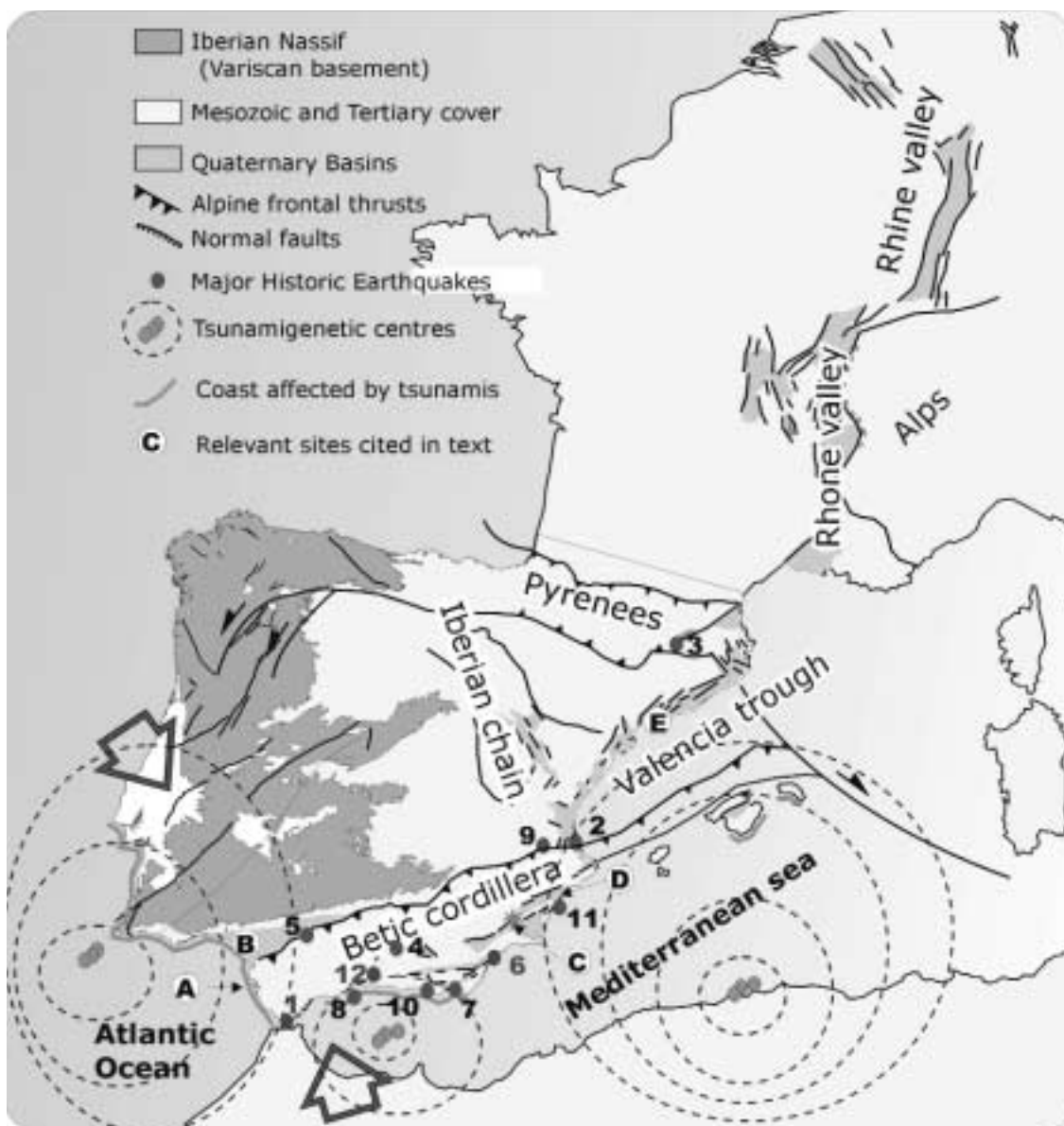
Fig. 1. Location of main historical earthquakes (≥ IX), tsunamigenetic centres and case studies in the Iberian Peninsula. 1. Baelo Claudia; 2. Tavernes; 3. Queralps; 4. Atarfe; 5. Carmona; 6. Vera; 7. Almería; 8 Málaga (tsunami); 9. Enguera; 10. Adra; 11. Torrevieja ; 12. Arenas del Rey (see table 1.). A: Valdelagrana spit-bar (Cádiz); B: El Abalario Dome (Huelva); C: Guadalentín Depression (Murcia); D: Lower Segura Basin; E: Catalan Coastal Ranges. Large arrows represent Quaternary and present orientation of the compressive stress generated by the Africa-Eurasia collision. The Gulf of Cádiz, Alboran Sea and Argelian tsunamifenetic centres (from west to east) are also highlighted .

stand how the human record it is incorporated to the geological one. This overlap zone extend (at the moment) in Spain from the 3rd century BC to the 13-14th Century BP. More modern events are fully documented in historical papers, letters, journals, etc.. and geological evidence is poor. Our present knowledge about the seismic history of a zone mainly comes from historical data. Recent works in archaeoseismology give us information of previously known and/or unknown seismic events, thus enlarging our seismic knowledge towards the antiquity.

SURFACE UPLIFT

Surface uplift refers to a process of altitude elevation in which tectonic and isostatic forces usually conjugate. Uplift operates over the landscape in the same way that a progressive regional base-level fall (increasing erosion) and/or favouring processes of fluvial defeating and pond-

ing (inundations), or opening of previously ponded ones. Uplift commonly operates on the landscape over time-scales up to hundred of thousands of years but some examples of landscape change are achieved in the Iberian littoral zone for the last 20,000 years. We will focus on the cases of the El Abalario zone (Atlantic coast-Huelva), and the Guadalentin Basin (Mediterranean coast –Murcia), which are well documented from the radiometric and archeological points of view .

The*Abalario zone* constitutes an elliptical topographic feature (Abalario Dome) closing the Guadalquivir-Doñana Marshlands to the SW. The littoral flank of the Dome is truncated by El Asperillo sea-cliff in which a well-preserved Late Pleistocene-Holocene sedimentary sequence has been analysed and dated (Borja *et al.*, 1999; Zazo *et al.*, 1999b; 2003). The sedimentary sequence is affected, and conditioned, by a large dip-slip fault subparallel to the coastline (Torre del Loro Fault: TLF), which defines an uplifted inland block broadly limited by the present sea-cliff. Active uplift in the zone is not apparently of pure tectonic origin, instead subsurface over-pressure conditioned by fluid/gas escape and coeval mud diapirism seems to drive the process (Zazo *et al.*, 2003). Uplift has been operating since the Late Pleistocene, when upwarping of the dome surface gave place to the initial obturation, diversion, and progressive eastward shifting of the Guadalquivir river system mouth. Subsequent accelerated upwarping facilitated the gravitational collapse of the littoral sector of the dome (TLF) and the generation of a similar cliff than today along the fault line during the Last Interglacial. The ancient cliff-line was eventually buried by successive aeolian deposition over the last glacial period until the middle Holocene (ca. 4,5 kyr BP), were a well developed iron crust sealed the aeolian sequence and the TLF line (Zazo *et al.*, 2003). The latest aeolian sequence, younger than ca. 14 kyr BP contains numerous interbedded organic-rich layers, which represents peat bodies (Zazo *et al.*, 1999). Around these wet zones early populations left behind a wealth of lithic workshops dated Late Neolithic-Copper Age (ca. 4.5 – 4.0 kyr BP). From this time headward erosion along adjacent cliff gullies eventually captured these shallow water bodies, and/or temporary wet zones, strongly limiting the fresh water availability in the area, conditioning their depopulation until recent times. In addition, also from this time (4 – 4.5 kyr BP) semi-mobile and mobile dune systems began to cover the area with successive periods of deposition in ca. 2,600 yr BP and 300 - 400 yr BP (Zazo *et al.*, 1999b; Borja *et al.*, 1999).

The *Guadalentin River Basin* represents a second example of significant demographic decay of ancient populations, conditioned by modification of the drainage presumably linked to tectonic uplift (Calmel-Àvila, 2000; 2002). The Guadalentin Basin constitutes a pre-littoral elongated depression, conditioned by one of the more active faults of SE Spain; the Lorca-Alhama de Murcia Fault (LAF). This tectonic depression has been subject to endorreic – semiendorreic conditions from the Late Pleistocene to 16th - 17th century, when engineering works eventually drained the zone (Silva *et al.*, 1996). Previously the depression was drained by two fluvial systems exerting contrasting aggradational and dissective effects. The ancient Guadalentín River (together important tributaries, such as Librilla, Lebor, etc..) coming from the Southwest ranges fed extensive lacustrine – palustrine systems located at the basin centre. On the other hand, the ancient Sangonera River had its headwater installed in the NE sector of the basin and was directed towards de Lower Segura Basin (NE), where it merged with the Segura River. The boundary (water divide) between these ancient river systems was located in a transverse rock-bar (El Romeral Pass) conditioned by a branched ramification of the LAF working as a blind fault. Lacustrine environments prevailed significant until ca. 4,500 – 4,300 yr BP, but endorrheic conditions done until the Late Copper Age (ca. 3,800 yr BP) when first evidences of dissection occur (Calmel-Àvila, 2002). However data of this same author indicate that major incision events (> 17 m) did not take place until ca. 2,500 yr BP (Iron Age). Recent carbon dates (unpublished) obtained from the basin centre support this hypothesis. Earlier incision processes favoured the capture, and progressive drainage (desiccation) of the middle Holocene extensive lacustrine environments. In each case, but mainly in the Late Copper Age, relevant demographic deteriorations occurred (Calmel-Ávila, 2002). On the other hand, the earlier incision episode is linked to the deformation of the Copper Age deposits. These are affected by a reverse flexure in the environs of the El Romeral Pass, which suggests that active upwarping was involved in this episode facilitating the propagation of headward erosion of the ancient Sangonera River and of its left bank tributaries (Ramblas of Librilla and Algeciras).

CONCLUSIONS.

Abrupt environmental changes promoted by earthquakes are rare and only became relevant signatures in the landscape from intensities up to IX-X MSK (magnitudes up to 6.5). For these intensities, in some cases secondary effects (landslides or tsunamis) can print in the landscape more important changes than the own primary effects (surface faulting), which hardly can condition the further geomorphological evolution. The Iberian Peninsula is subject to low-moderate seismicity mainly linked to low-slip faults (0.02 to 0.2 mm/yr). Recorded intensities of major historic earthquakes do not surpass X MSK, and estimated magnitudes of recorded historic and prehistoric events range between M 6,5 - 7,0. These values are considered too low to produce noticeable permanent change in the landscape. Only in the last strong earthquake occurred in Spain (1884 AD Arenas del Rey Earthquake; IX MSK) is surface faulting still a prominent visible feature in the landscape. Even in the case, of extensive tsunami damage affecting to the Atlantic littoral of Iberia (i.e. 1755 AD Lisbon Event) recorded changes are minor, and whatever the case never a prominent permanent feature in the landscape. On the Spanish littoral this major event (Ms 8.5 - 9) was only recorded as modest washover fans breaking the more recent spit-bar systems in the Gulf of Cadiz. The Baelo Claudia events (40-60 AD and 350-395 AD) represent the unique archeoseismic evidence of strong seismic damage reported for the Iberian littoral.

Other processes related with active tectonics, such as surface uplift, can promote upwarping of the ground surface. When active upwarping interfere with the fluvial system, dramatic environmental changes can give place to relevant demographic changes. Cases illustrated in this work, deal with the fluvial capture and desiccation of ancient Holocene wetlands (peats and/or palustrine zones) presumably providing fresh water for Late Neolithic/Early Copper Age populations. In both cases (Huelva and Murcia) relevant environmental changes between 4,000 and 2,500 yr BP coincide with the eventual post-flandrian sea-level fall in the Spanish littoral and with the so called 3rd millennium climatic (aridity) crisis of the Mediterranean, that produced similar effects on ancient wetland zones located in northern Africa (Petit-Marie, this volume).

Santorini and Nisyros: similarities and differences between the two calderas of the modern Aegean Volcanic Arc

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The Aegean Volcanic Arc, extending along the islands of Poros, Methana, Milos, Santorini, Yali, Kos and Nisyros (Fig. 1), is the result of northeastward-directed subduction of the Eastern Mediterranean lithosphere below the active Hellenic margin of the European plate (Papanikolaou, 1986) (Fig. 2). Santorini and Nisyros are the most recent active volcanoes in the Aegean Volcanic Arc, located at the centre and the eastern edge of the arc, respectively. Although Nisyros displays a spectacular geometry of volcanic scenery, it is the least-known and least accessible of all Mediterranean volcanoes in contrast to Santorini, which is world-famous both for its volcanic structure and its impact on human civilization.

Fig.1. Simplified map of the present day geodynamic structure of the Hellenic Arc.

Nisyros

Volcanic activity is known in the area of Kos-Nisyros since Late Miocene-Pliocene times. One of the largest eruptions in the Eastern Mediterranean, manifested by the outcrops of the "Kos ignimbrite", occurred 165,000 years ago (Keller *et al.*, 1990), producing more than 100 km^3 of ashes, pumice and pyroclastics flows, devastating an area of about 3000 km^2. The center of this catastrophic eruption is not known with accuracy but it is probably located in the submarine area of Yali islet, north of Nisyros.

The island of Nisyros is composed exclusively of Quaternary volcanic rocks with alternating lava flows, pyroclastic layers and lava domes, ranging in age from 200 to 25 ky. Alpine basement rocks are detected at depth (-1,800 m) from geothermal drillings. It forms a truncated cone with a base diameter of 8 km with a caldera of 4 Km diameter. The evolution of this volcano is divided in five major stages (Martelli, 1917; Desio, 1931; Davis, 1967; Di Paola, 1974; Papanikolaou *et al.*, 1991): 1) An underwater volcano, which erupting basaltic and andesitic pillow-lavas, built up the lower volcanic rocks visible on the northern coast near Mandraki; 2) A 500-700 m high stratovolcano grew, on top of these partly submarine lavas, for a period of more than 100,000 years; 3) After many eruptive phases of gas and steam explosions, two major rhyodacitic plinian eruptions deposited huge volumes of pyroclastic flows and pumice covering the whole island; 4) Subsequently a major collapse of the volcano followed, leaving a large caldera behind it and 5) The western part of the caldera depression was filled up, during pre-historical times, by a series of rhyodacitic domes, the highest of which, Profitis Ilias, rises about 698 m above sea-level.
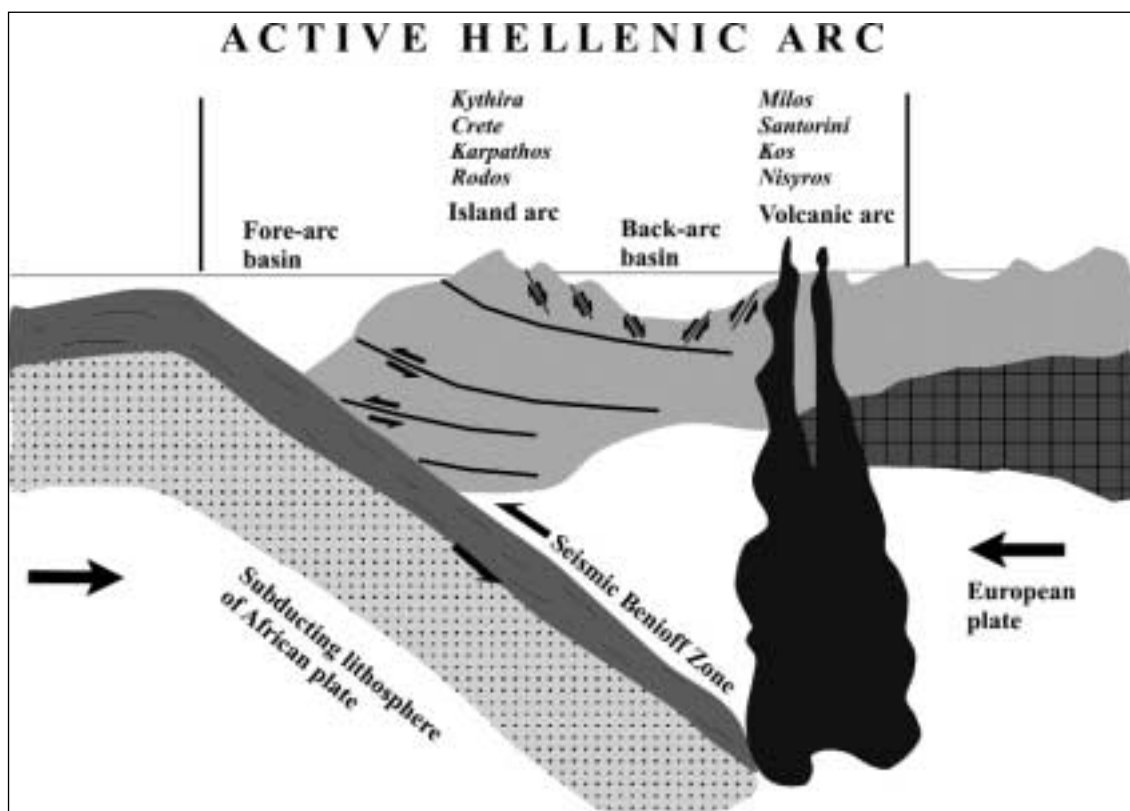

Fig. 2. Schematic profile showing the subduction of the East Mediterranean lithosphere.

No volcanic activity is known to have occured on the island after the formation of the domes for at least 25.000 years; the only historical explosions mentioned are related with the formation of several craters inside the caldera, such as Alexandros, Polyvotis, Stephanos, Phlegethon and Achelous, which are still emitting fumaroles. Violent earthquakes, gas detonations, steam blasts and mudflows accompanied the most recent hydrothermal eruptions in 1871-1873 and 1887 (Marini *et al.*, 1993). No casualties were reported during this volcanic activity, although some people were slightly injured and minor damages were caused in the houses.

The fact that there are no reports of volcanic activity in the area by the classical authors suggests, but does not of course prove, that the main eruptions on Nisyros were over by the time the classical Greek texts were written. Archaeological evidence shows that the main cone and caldera were formed before 1200 BC. The ruined "Pelasgian" fortress of Mycenaean type, 1 km south of Mandraki, was built on the pyroclastics that erupted in the great plinian eruptions (Scarth 1983). Astrom (1978) reports that Neolithic artifacts which have been found within the Nisyros caldera,would push back its formation to, at least, a Neolithic age.

Recently, in the submarine area around Nisyros, new individual submarine volcanic centres have been discovered with swath multibeam mapping and seismic tomographic profiling (Nomikou and Papanikolaou, 2000), most of them emerging locally as small volcanic islets around Nisyros. The new submarine volcanoes revealed exhibit a different geometry and evolutionary stage. The lack of sediments overlying the volcanic domes indicates their very young age, ranging between Upper Pleistocene and Holocene. The compilation of topography and swath bathymetry enchances the visual presentation of the whole volcanic field as in Fig. 3, where the crater of Nysiros volcano is very clearly expressed by the circular depression in the middle of the island.

Papanikolaou D., Nomikou P., Alexandri M., Ballas D. 2003,
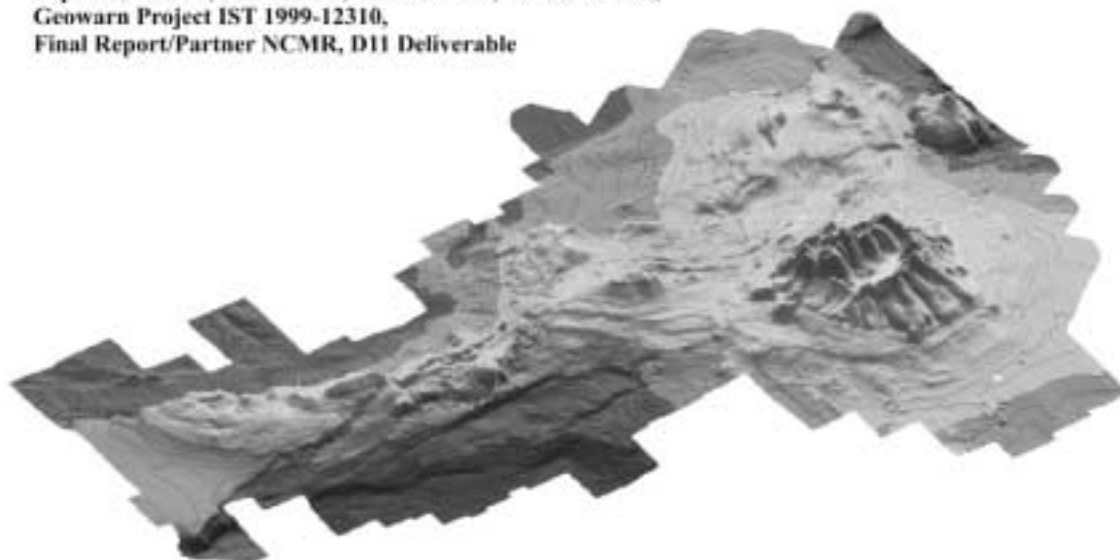Geowarn Project IST 1999-12310,
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Fig 3. 3-D perspective diagram of Nisyros volcanic field viewed from south.

Santorini

Santorini which was a small non-volcanic island, was developed on a basement formed of late Mesozoic-early Cenozoic schists and marbles exposed in Profitis Ilias Mt (Druitt *et al.*, 1989). Volcanism in the area of Santorini, started 2 million years ago with the extrusion of dacite vents on the Akrotiri Peninsula and continued producing different kinds of lavas and pyroclastics (Friedrich, 2000). However, the most characteristic type of activity over the last 200,000 years has been the cyclic construction of shield volcanoes interrupted by large explosive and destructive events like the Minoan eruption, one of the biggest eruptions in human history. Witness of this activity is the ring-shaped sea-flooded caldera, 8x10 km in size and 250-400 m in depth, enclosed by Thera, the Therasia islands and Aspronisi islet. Palea and Nea Kameni were later formed within the caldera by several eruptions during historic and recent times.

Excavations beneath the Minoan ash- layer, started since 1969 by Prof. Marinatos, brought to light an important cycladic town with well-preserved wall paintings, ceramics and other finds. The archeological findings near Akrotiri clearly demonstrate that during the Late Bronze Age the island was vibrant with life and movement, enjoying a prosperous civilization similar to that of Minoan Crete. It was a richly developed and probably oligarchic maritime community whose

flourishing economy was provided by intensive trade, shipping and probably vine, like at present (Doumas, 1983). At that time, Thera was a ring-shaped island, a central shield volcano with hot springs and a cauldron caldera with an opening southwestwards, between Aspronisi and the cape of Akrotiri peninsula. The spectacular discovery induced continuing speculations that the volcanic destruction of Santorini forged the legend of the sunken Atlantis, a prosperous continent or island that sunk and disappeared into the sea (see Luce, 1969), as told many times since Plato.

The Minoan eruption on Thera was a major Plinian caldera-forming event that happened around 1640 B.C. (Hammer *et al.*, 1987) and continued over months or years. It is divided into four distinct phases: 1) Plinian phase, 2) phreatomagmatic base-surge 3) ash-flow phase and 4) non-welded ignimbrite (Bond and Sparks, 1976; Pichler and Friedrich, 1980; Druitt and Francaviglia, 1992). It erupted 30-40 km^3 rhyodacite magma and the height of the plinian eruption column is estimated up to 36-39 km (Pyle, 1990). The dispersed Minoan tephra is found throughout the Eastern Mediterranean and might have led to global climatic impacts. The eruption was followed by collapse of the magma chamber up to 800 metres down, and enlarged the existing caldera causing massive sea level fluctuations. These giant waves devastated all surrounding Cycladic islands and most of the south Aegean coasts, and destroyed the towns of Mallia, Phaistos and Kato Zakro in south Crete. The Minoan eruption is estimated to have been five times more powerful than the one of Krakatoa, producing a high eruption cloud and generating tsunamis of 60-100 m high. So it is quite possible to believe that the city of Knossos, located just 90 km away in northern Crete, could have been destroyed by this event, covered by thick volcanic ash layers.

No human body has been found killed by the eruption. Apparently local populations had been warned by earthquakes and water explosions, which were considered omens sent by infuriated gods. The exodus was apparently not hasty, as neither valuable objects nor furniture were left behind. There were no close eyewitnesses of the eruption that could survive and give a direct report, but grass found on the roofs of buildings, which were destroyed later, indicates that at least one rainy season went by, between evacuation and the actual volcano eruption (Dietrich, 2000).

The volcano of Santorini activated again during historic times, building the dark-colored lava shields of Nea and Palea Kameni inside the caldera. Compared with the Minoan, these eruptions were very small and they did not cause any death. The ancient writer Starbo is the first to mention volcanic eruptions inside the caldera; he described the rising of a new small island, probably a precursor of Palea Kameni during the year 197 B.C. Thereafter, at least eight eruptive phases followed in the years 46/47 A.D., 726, 1570-1573, 1707-1711, 1866-1870, 1925-1928 (Fig. 4), 1938-1941 and 1950, the most recent eruption. At present, only fumarolic activity is visible at Kameni islets which are visited daily by hundreds of tourists during the summer season.

Fig. 4. Dafni Eruption (Nea Kameni,) 23 October 1925.

It is noteworthy that besides the famous Minoan eruption of Santorini, the most destructive recent volcanic eruption occurred on Columbo on 27 September 1650 with extrusion of ash, pumice fall and toxic gasses that caused more that 50 fatalities and the generation of a strong tsunami. Today, its appearance is a circular caldera, 2 km in diameter, created apparently by the collapse of a relevant volcanic cone. The rim of the caldera with an almost indented perimeter stands at about 150 m depth, while its flat bottom which does not exceed 1 km in diameter, lies at a depth of 504 m (Fig. 5).
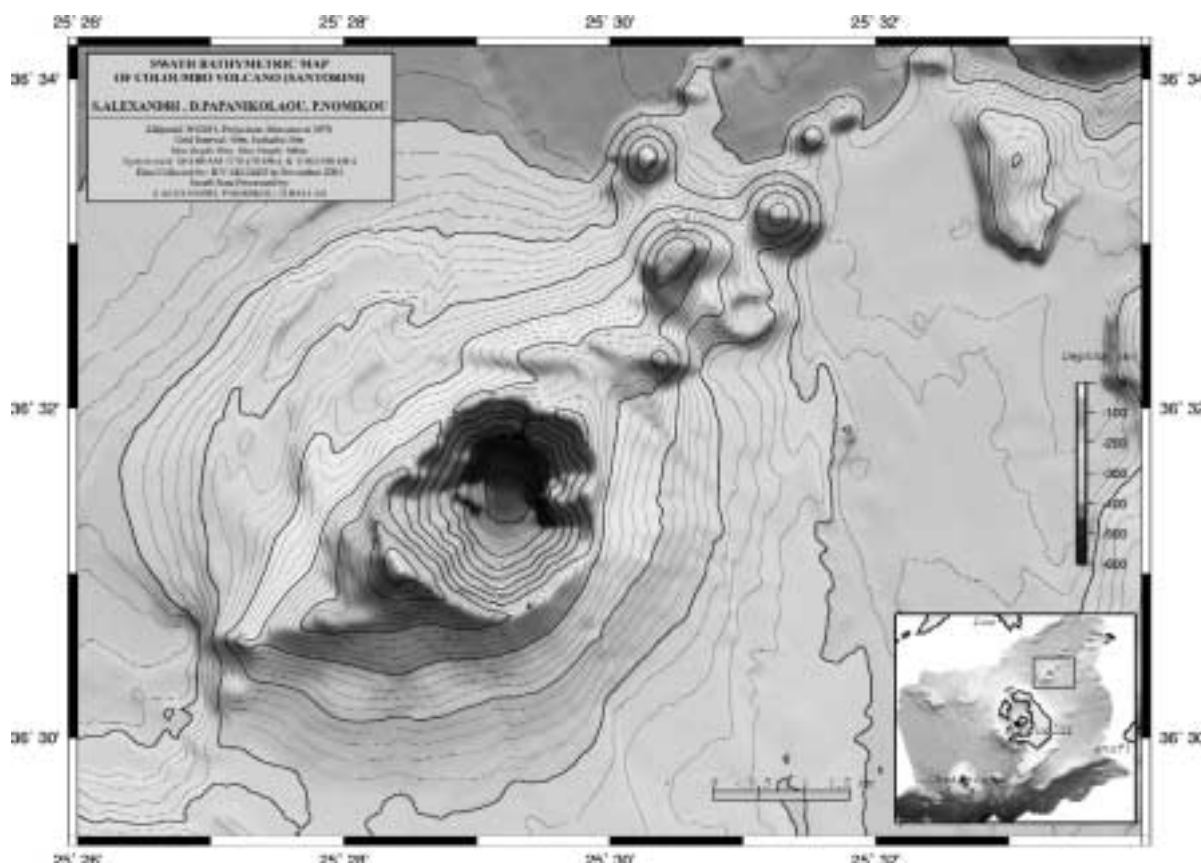
Fig. 5. A swath bathymetric map of Coloumbo submarine volcano, NE of Santorini.

Comparative remarks

Nisyros and Santorini are the most active volcanoes in the Aegean Volcanic Arc, displaying a different stage of caldera structure. In Nisyros, after the major collapse of the existing stratovolcano, the resulted caldera was never drowned by the sea (base of caldera at + 80m). In contrast, in Santorini, during the Minoan eruption, the crater collapsed down to 800m, the caldera was violently broken, cut into several parts and flooded by seawater in the center (base of caldera at - 400m).

The alpine basement in Santorini is exposed on Profitis Ilias Mt, at an altitude of 550 m, whereas in Nisyros there is no evidence of it on land although it has been detected in 1,800m below sea level by drillings in the central part of the caldera.

The post-caldera evolution in Nisyros comprises massive dacitic-rhyodacitc domes with the highest, Profitis Ilias, rising about 698 m above sea-level. On the contrary, in Santorini the dark-colored lava shields of Nea and Palea Kameni islands have been built inside the caldera, about 100 m above sea level. In Nisyros the top of the post-caldera domes are 300 m higher than the caldera rim, whereas in Santorini they are 200 m lower.

In Thera, the rich and unique civilization which was flourishing before the great Minoan eruption, violently vanished, covered under huge masses of pumice, and the island was abandoned for many decades. Quite the opposite occurred in Nisyros, where according to archaeological evidence, there was no volcanic disruption of the local civilization, since the neolithics.

During the Holocene volcanic activity is very low on Nisyros but very intense on Santorini.

The fatalities from the volcanic activity are in general very small in both islands; the most destructive event was the Columbo eruption in 1650. It is remarkable that both islands have suffered much more, with casualties and collapse of houses, by earthquakes not related to the volcanic activity (1931 in Nisyros, 1956 in Santorini).

Evidence from recent oceanographic surveys of a last rapid sea level rise of the Black Sea

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In 1997, Ryan and Pitman (Ryan *et al.*, 1997) came forward with astonishing evidence suggesting that a catastrophic flood of the Black Sea 7,500 years ago could have played a primordial role in the spread of early farming into Europe and much of Asia. In 1999, in their book *"Noah's Flood, the new scientific discoveries about the event that changed history"* (Ryan and Pitman, 1999b) these two authors stated also that this flood could have cast such a long shadow over succeeding cultures that it inspired the deluge account in the Babylonian epic of Gilgamesh and, in turn, the story of Noah in the Book of Genesis.

This hypothesis arose from the results of a joint Russian-American expedition carried out in 1993 on the continental shelf south of the Kerch Strait and west of Crimea (Major, 1994; Ryan *et al.*, 1997). These results were established from interpretation deduced from high-resolution seismic reflection profiles, cores precisely targeted on these profiles and on dating by carbon-14 Accelerator Mass Spectrometry of the informative layers. The survey revealed a buried erosion surface strewn with shelly gravel extending across the broad continental margin of the northern Black Sea to beyond its shelf break (Evsylekov and Shimkus, 1995; Major, 1994). The cores recovered evidence of sub-aerial mud-cracks at -99 m, algae remains at -110 m, and the roots of shrubs in place in desiccated mud at -123 m. Each site lay well below the -70-m level of the Bosphorus bedrock sill (Algan *et al.*, 2001; Gökasan *et al.*, 1997). This combination of evidence suggested to Ryan *et al.* that a drowning event in the Black Sea could be the consequence of a steady transgression on a vastly shrunken lake characterised by the deposition of a uniform drape of marine mud on the terrestrial surface equally thick in depressions as on crests of dunes with no sign of landward-directed onlap of the sedimentary layers in the drape (Ryan *et al.*, 2003). The ^{14}C ages documented a simultaneous sub-aqueous colonisation of the terrestrial surface by marine molluscs at 7,100 y BP*·. This age was assigned to the Holocene flooding event. However, flooding precludes the possibility of outflow to the Sea of Marmara during the prior shrunken lake

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* y BP means years before present (1950) without neither correction for reservoir age nor calibration to calendar years. In Ryan et al. (1997) and Ryan, W. and Pitman, W., 1999a, ages were expressed in calendar years with 7,500 cal y BP equivalent to 7,100 y BP.

stage. Arguments for persistent Holocene outflow from the Black Sea to the eastern Mediterranean (Aksu *et al.*, 2002b) and for noncatastrophic variations in Black Sea sea level during the 10,000 y BP (Aksu *et al.*, 2002c) have been recently presented to contradict the flood hypothesis. In order to evaluate the validity of the catastrophic model or its replacement by a continuous outflow model, our review cites many papers published in the Soviet literature that contain pertinent observations and discussions not considered in arguments against catastrophic flooding.

More recently, in 1998 and 2002, two Ifremer oceanographic surveys completed the results from previous studies of seabed mapping and of subsurface sampling realised by Soviet scientists and various international expeditions. These recent surveys carried out on the north-western continental shelf of the Black Sea established that the Black Sea's lake level rose on the shelf to at least the isobath –40 to 30 m given by the landward limit of extend of the Dreissena layer characteristic of freshwater conditions. This rise in freshwater level would coincide with the functioning of the Black Sea as an important catchment basin of the melt water drained from the melting of the ice cap ensuing the Melt Water Pulse 1A , from the Bølling Allerød period (Bard *et al.*, 1990). It is possible that at that time the lake level filled by freshwater rose to the level of its outlet and spilled into the Mediterranean. However, in mid-Holocene at 7,500 y BP the onset of salt water conditions are clearly evidenced in the Black Sea. While this hypothesis has been discussed (Aksu *et al.*, 2002a; Aksu *et al.*, 2002b; Aksu *et al.*, 1999b; Aksu *et al.*, 2002c) the recent discoveries of the excellent preservation of drowned beaches, sand dunes and soils seem to bring credibility to the Ryan and Pitman assumption.

GEOLOGICAL BACKGROUND

The Black Sea is a 2.2 km deep basin with a broad northwest continental shelf (Fig. 1). Connection to the external Mediterranean Sea is over a sill in the Bosphorus Strait. The role that this strait has played in controlling the salinity and stratification of both seas to produce intervals of anoxia has been discussed widely (Abrajano *et al.*, 2002; Arkhangelskiy and Strakhov, 1938; Lane-Serff *et al.*, 1997; Muramoto *et al.*, 1991; Rohling, 1994; Scholten, 1974). The general view is that during periods of low global sea-level the Black Sea lost connection with the ocean, freshened from river discharge into a vast lake, became well ventilated and established a shoreline at the level of its outlet (Chepalyga, 1984; Hodder, 1990) in order to export excess water to the Mediterranean.
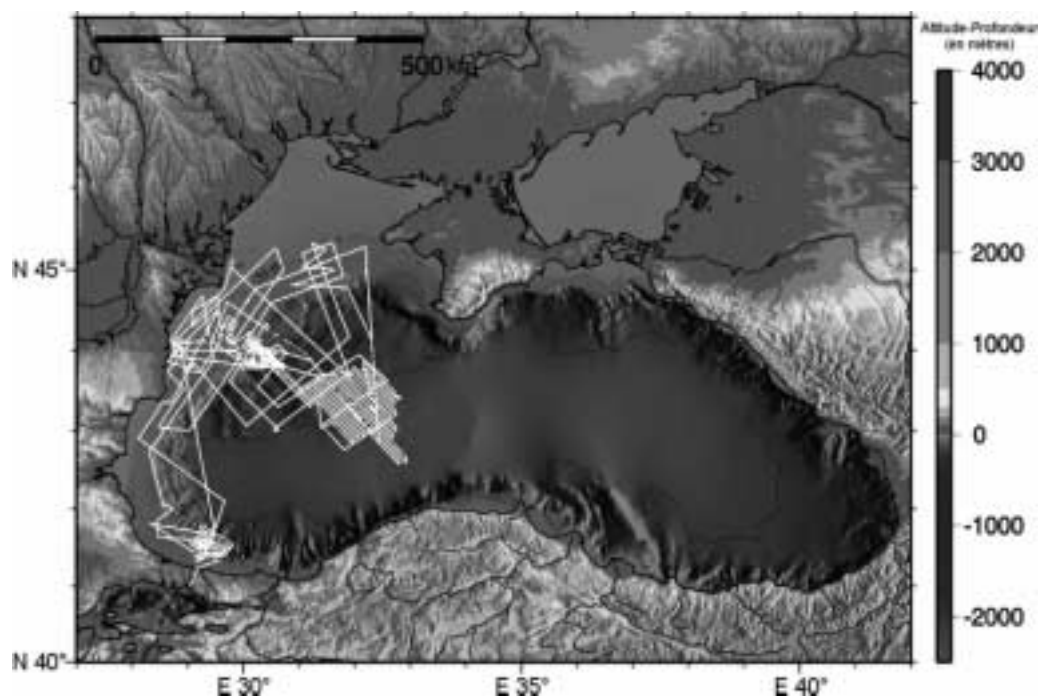

Fig. 1**.** Bathymetry of the Semi-enclosed Basin Black Sea and rooute location of the Ifremer surveys.

The North-western Black Sea receives the water and sediment discharges of the largest European rivers (Danube, Dniepr, Dniestr). For instance, the drainage basin of the river Danube is of 817,000 km². The Danube multiannual water discharge into the Black Sea is estimated at 6,047 $m^3.s^{-1}$ (almost 190 $km^3.yr^1$), while its multiannual sediment discharge at the mouth zone was of about 51,7 million tons per year (t/yr) before the river damming (Bondar, 1998). After the damming in 1970 and 1983, one can estimate that the Danube total average sediment discharge could not be larger than 30-35 million t/yr, including only 4-6 million t/yr of sandy material (Panin, 1997). During the glacial lowstands and especially at the beginning of interglacials, the sediment discharges of these rivers were probably much higher.

It has long been recognised that the Black Sea was isolated from the Marmara Sea and the Mediterranean during glacial intervals when levels of the latter seas fell below the sill depth (at –35 m) of the Bosphorus. Similarly, it has been postulated that the water level of the Black Sea rose along with the Marmara and Mediterranean seas once their water levels rose above the Bosphorus sill depth (Degens and Ross, 1974). However, recent analyses of sediments deposited along the margins of the Black Sea suggest that water level fluctuations in the Black Sea were somewhat more complex, with high lake levels occurring during wet, late glacial intervals and low lake levels occurring during drier early interglacial times (Chepalyga, 1984).

Another widely-accepted hypothesis on the connection of the Black Sea with the external oceans postulates that this inland sea had always maintained a continuous outflow through the Bosphorus and Dardanelles Straits, even during the highly arid glacial intervals (Chepalyga, 1984; Kvasov and Blazhchishin, 1978). Essentially, it was assumed that the river input to and precipitation on the Black Sea have continuously exceeded any loss from local evaporation. Indeed, meltwater from former ice caps in Fennoscandia, northern Asia (Grosswald, 1980) and the central Alps has transformed the Black Sea into a giant freshwater lake a number of times in the past (Federov, 1971; Ross *et al.*, 1970) and most recently during the Neoeuxinian stage of the Late Pleistocene (Arkhangelskiy and Strakhov, 1938; Federov, 1971; Nevesskaja, 1965; Nevesskaja and Nevesskiy, 1961; Ross *et al.*, 1970) (Fig. 2).

Ryan *et al.* (1997) published evidence that during the last Quaternary glaciation, the Black Sea became a giant freshwater lake. This evidence includes new AMS ^{14}C dates, abrupt changes in
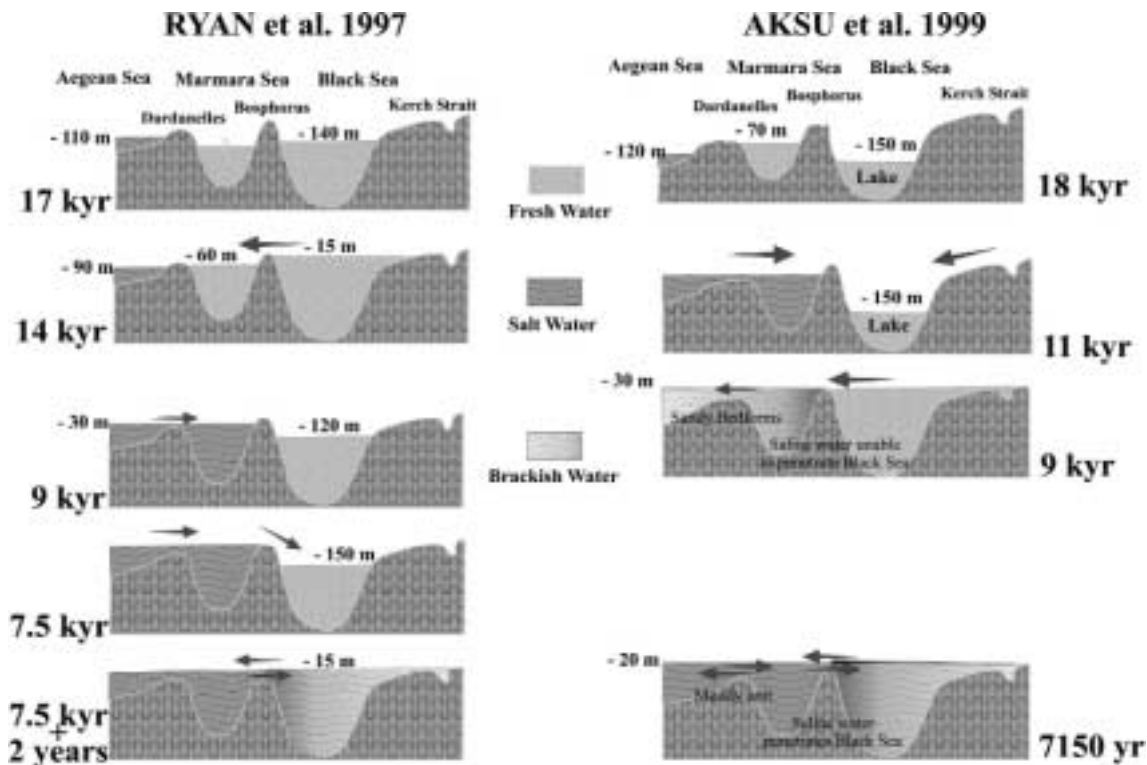

Fig. 2. Controversal schemes of the reconnection between the Black Sea and the Mediterranean.

the organic carbon content, water content and $D^{18}O$ of core material at about 7,150 y BP, as well as the occurrence of a widespread unconformity interpreted as an erosional surface subaerially exposed during the last glacial. From the depth distribution of the unconformity, the surface of this freshwater lake must have fallen to levels >100 m below its outlet. By about 7,150 y BP, the sill depth of the Bosphorus was breached and a catastrophic flooding of the continental shelf of the Black Sea was inferred (Fig. 2).

One piece of evidence that argues against catastrophic flooding is the different ages of sapropels in the eastern Mediterranean and the Black Sea. Sapropel S_1 in the Aegean is commonly taken to be deposited from about 9,600 to 6,400 calendar years BP (Aksu *et al.*, 1999a; Aksu *et al.*, 1999b; Fontugne *et al.*, 1994) but deposition could have lasted to 5,300 y BP (Rohling and de Rijk, 1999). During this time, nutrient-rich freshwater from the Black Sea reduced the surface salinity of the eastern Mediterranean, thus increasing the stability between the surface and deep waters and decreasing deep circulation (Aksu *et al.*, 1999a). High surface productivity and circulation stagnation are conditions favourable for sapropel formation. In the Black Sea, on the other hand, sapropel formation started about 550 years later than in the eastern Mediterranean (Rohling, 1994), when the denser Mediterranean waters displaced the nutrient-rich waters in the Black Sea towards the surface (Calvert, 1990; Calvert and Fontugne, 1987). This lag is probably too large to be accounted for by the catastrophic flooding hypothesis.

ARCHEOLOGICAL APPROACH

The impact of climate on human evolution and development has long been discussed (e.g., (Stanley and Galili, 1996). Archaeological excavations in many areas of the eastern Mediterranean (Ammerman, 1989; Perlès, 2001) are uncovering evidence relating the emergence and spread of early farming communities, as related to environmental and social factors. It is assumed (Cita *et al.*, 1984) that the spreading of agriculture into the Western Mediterranean may have been initially induced by a cold event dated to 8,200 cal y BP (ca 7,500 uncorrected radiocarbon y BP), identified, for example, in the ice-core records of Greenland (Alley *et al.*, 1995) and marine records of the north Atlantic (Dahl-Jensen *et al.*, 1998; Strohle and Krom, 1997; von Grafenstein *et al.*, 1998).

However, the recent data analysed in the Black Sea cores relate to a very rapid change in the environmental and climatic conditions around the Black Sea lake. This could have induced an environmental stress for well-established and growing farming communities and resulted in forcing them to explore other areas outside Southwest Asia. This younger event is coincident with the introduction of euryhaline molluscs into the Black Sea to replace those of its Neoeuxine fresh to brackish lake (Lericolais, 2001; Ryan *et al.*, 2003; Ryan and Pitman, 1999b; Ryan *et al.*, 1997). However, evidence of a short-term cooling during Sapropel level S1 and dated at 7,500 cal y BP is surfacing in various areas of the Mediterranean (Ariztegui *et al.*, 2000; Emeis *et al.*, 2000; Lane-Serff *et al.*, 1997; Martinez-Ruiz *et al.*, 2000; Mercone *et al.*, 1999).

On the other hand, agricultural communities were established across Europe between 8,000 and 5,000 years ago. The best evidence currently available to archaeologists indicates that two different processes were involved: the colonisation of new habitats by populations of farmers and the adoption of agriculture by indigenous foragers (Bogucki, 1996). Despite efforts of archaeologists to clarify which of these processes was active in a particular region, there is still considerable regional debate between those who favour colonisation and those who argue for in situ development. The presence of domesticated wheat, barley, sheep, and goat unequivocally provides the vector for the Neolithic Diaspora in Europe. Since these species exist in their wild form only in the Near East, their dispersal was clearly from the south-eastern corner of Europe to the Northwest and to the west. Domestic livestock, of course, can move on their own, and the role of feral animals in expanding the range of domesticated species in Europe cannot be overlooked (Bogucki, 1996).

First colonisation of Near East Neolithic population is known to be around 8,200 cal y BP. These first population came through the Anatolian mountains with their domesticated wheat, barley, sheep, and goat and settled around the Aegean coastal zone. A second wave of colonisation

appeared 100 years later, when these farmers decided to move into land generally following river courses (Lichardus and Lichardus-Itten, 1985). This gradual migration of farmers up the Danube Valley into central Europe represents one of the most striking events of the Neolithic period in Europe. These new settlers stayed fairly close to the banks of the river and its tributaries (Greg, 1988).

Around 7,500 cal y BP these Neolithic population gave birth to two population movements in Europe. One is the Danubian movement colonising all the North of Europe from Romania to the Paris basin through Hungary. They eventually occupied through the following millennium half of the North of Europe. The Neo-Balkanian painted pottery shows definite Asiatic similarities; there was painted pottery in Iraq in the earliest known cultures; Anatolia contains some varieties of it; the Iranian plateau is said to be full of it; there is painted pottery at Anau in Turkestan; and painted pottery penetrated early into Kansu in China.

The second population movement, usually called the Mediterranean movement (Fig. 3) had developed all along the Mediterranean coast (Malville *et al.*, 1998) until the Catalonian littoral before moving northward along the Rhone river valley (Hodder, 1990). Despite these occurrences, Archeologists do not yet know by which route or routes it entered Europe from the east. It may have come across the Bosphorus, around the Black Sea, or from both quarters. Again, it may have travelled, farther east, either north or south of the Caspian.
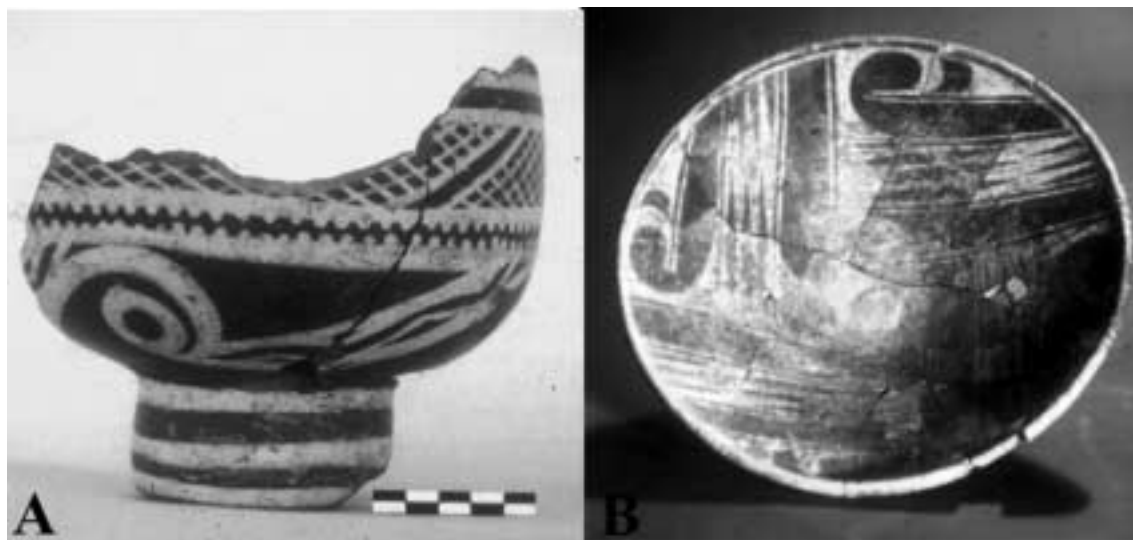

Fig. 3. **A.** Early-Neolithic from Kovacevo in Bulgaria (French-Bulgarian survey) (Photo by J.P. Demoule). **B.** Vase with golden ornaments from the Earlier Chalcolithic period of the Varna Necropolisin Bulgaria (from the Varna Archaeological Museum: http://www.varna-bg.com).

OBSERVATIONS

Topography

Bathymetry data were provided by multibeam echosounder (Fig. 4). Prominent in the northern half of the survey area are linear ridges four to five meters in relief and with an average spacing of 750 m. They strike almost uniformly at an azimuth of $75 \pm 10°$. The ridges are typically asymmetrical in cross-section with steeper sides facing to the Southeast. The ridges have a length to width ratio exceeding four. In addition, some tens depressions with diameters from 100 to 1800 meters and a negative relief of 3 to 9 meters populate the southern half of the corridor. Depths of individual depressions are greatest at the base of their Northeast walls and they shoal to the Southwest. In the centre of the surveyed corridor some depressions align in troughs between the linear ridges.

Subsurface structure

The ridges and depressions can be viewed in cross-section by very high resolution seismic reflection profileschirp system sweeping from 4 to 16 kHz. These tools (sub-bottom profiler and
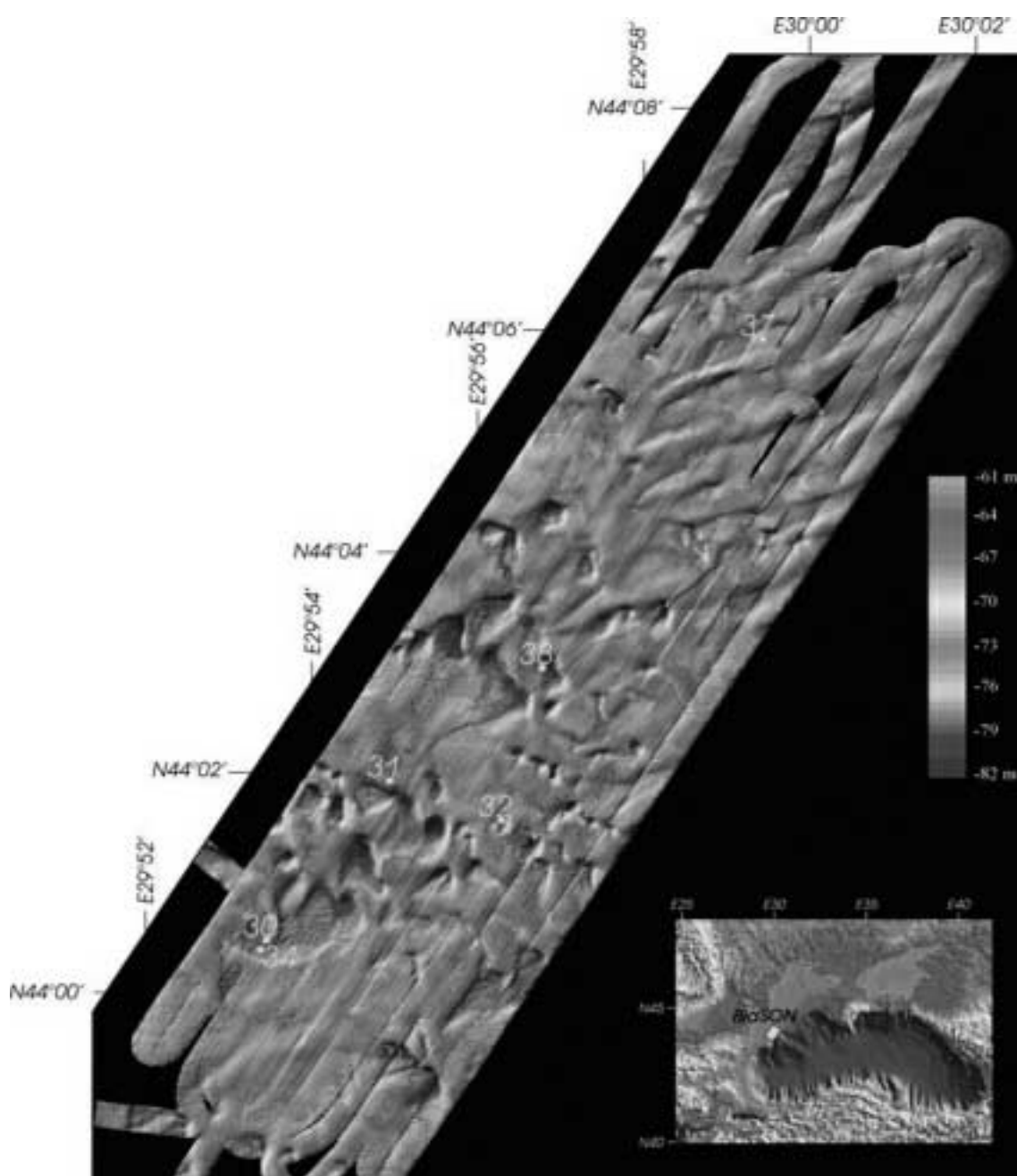
Fig. 4. The multibeam bathymetry covering a sand dune field.

Chirp sonar) provide a penetration to tens of meters and a definition of layering at the sub-meter scale. The profiles show that the ridges in the north are asymmetrical and with only one exception have their steeper side facing to the Southeast. These ridges are superimposed on a reverberant "bottomset" reflector that is sometimes conformable with subjacent strata but in many cases truncates them (Fig. 5). The high ground in the south has the appearance of a mound though it is also asymmetrical in cross-section with the crest and steeper slope predominantly on the south side. The interiors of the ridges and mounds contain steeply-dipping "foreset" clinoforms with the same asymmetry and orientation as the cross-section topographic profiles.

Everywhere across the mid and outer shelf the ridges, mounds and depressions are draped by a thin layer of sediment with a remarkably uniform thickness of no more than one meter (Fig. 5). The linear ridges surveyed in this study are aligned somewhat obliquely to the regional bathymetric contour and to the paleo-shoreline outlined by wave-cut terraces (Fig. 6).
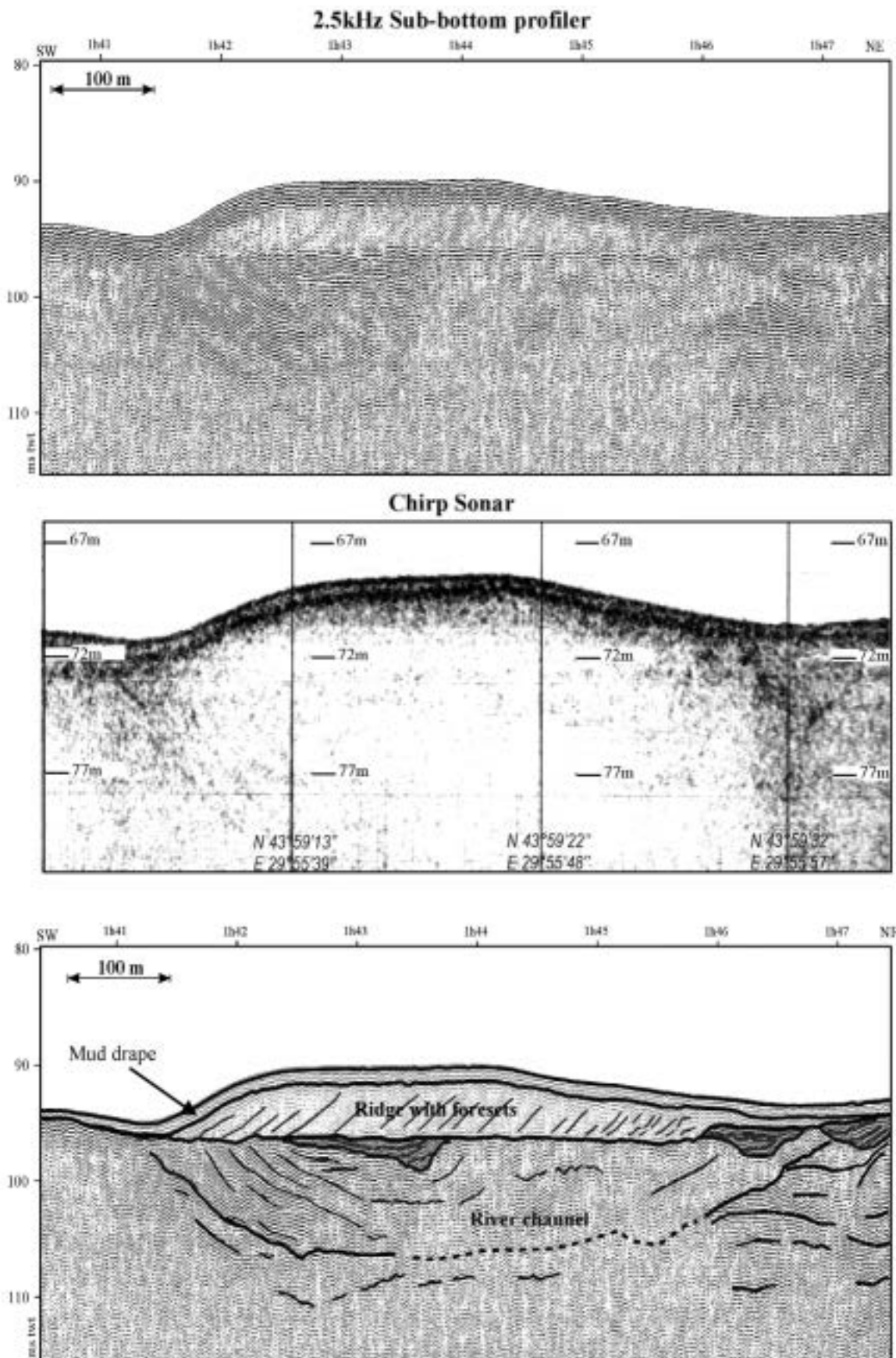
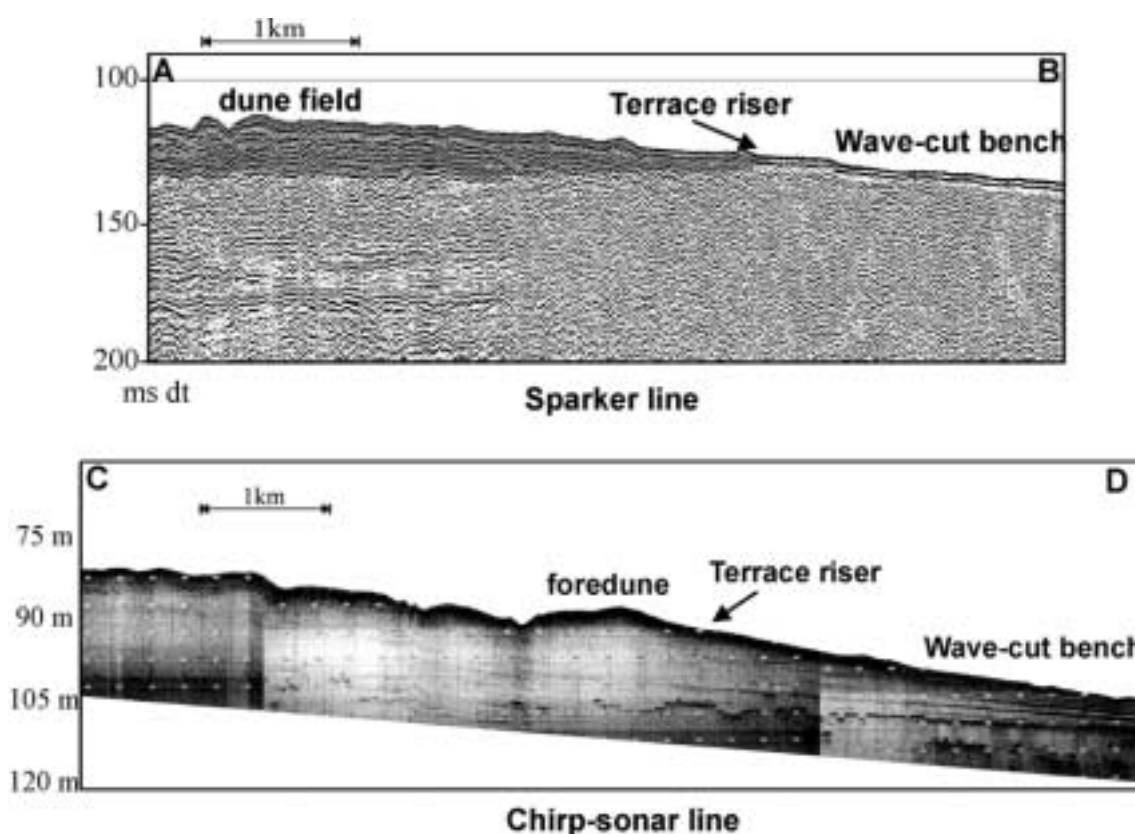Fig. 5. Seismic profiles across a sand dune.

Fig. 6. Seismic profiles across the wave cut terrace.

Sediment cores

Sediments, obtained by coring methods, provide ground truth to the reflection profiles. Sampling into the interior of a ridge recovered dark sand rich in opaque heavy minerals and shell fragments (Fig. 7). The minerals include quartz, garnet and ilmenite. The shell fragments are those belonging the fresh-water mussels of the *Dreissena* species. Cores into the bedded sediments on which the dunes have formed consist of silty red and brownish clay with thin lenses containing fresh to slightly brackish water molluscs (*Dreissena* and *Monodacna* sp., respectively). These specimens return AMS radiocarbon dates spanning 8,585 to 10,160 ± 90 y BP (without reservoir and dendrochronologic calibration).

Molluscs within the uniform surface drape recoved in the BlaSON cores are exclusively saltwater species such as *Mytilus edulis* (also known as *Mytilaster*) and *Cerastoderma edule*. Those sampled near the base of the drape date in the range of 6,590 and 7,770 ± 80 y BP.

Within the cores that penetrate through the drape, basal contact is sharp with organic rich marine-mollusk bearing mud above, and a sand of variable thickness below rich with remains of *Dreissena* sp. Further, palynology analysis and studies of the dynokysts population realised by Speranta Popescu (Popescu, pers. comm.), detail a real onset of freshwater arrival during the Younger Dryas and abrupt replacement of Black Sea dynokyst by Mediterranean population at 7,150 y BP.

DISCUSSION

The Sand dune fields and its wave cut terrace is interpreted as a coastal zone relict. This environment spanning the interval from 9,680 to 8,360 yr in a coastal setting with a wave-cut terrace at –100 m and dunes and pans between –80 and –65 m would have lain well below the level of the external ocean (Fairbanks, 1989). A lake below global sea level is only possible with a Bosphorus barrier shallower than the external ocean and the absence of outflow. The burial of the
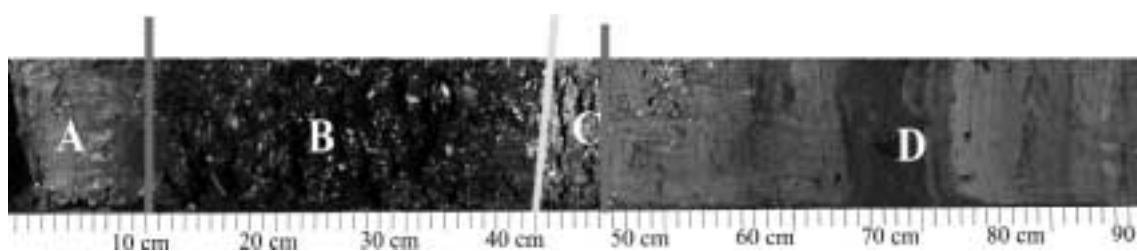
Fig. 7. Core recovered on the Dune field. **A.** Layer with Modulus dated from 3,000 yBP to present. **B.** Layer with *Mytillus Edulis* (6,900 to 3,000 yBP). **C.** Layer with *Dreissena*, the youngest is aged of 7,500 y BP.

dunes and pans by a drape of mud does not alone require a sudden filling of the depression once the Bosphorus barrier was breached. But taken with evidence of an abrupt passage from the shell hash to mud, a very condensed layer with brackish fauna only populating the shell hash substrate, and the impressive preservation of the dunes and pans with no preferential infilling of the depression, the evidence seems compelling for a rapid Black Sea terminal transgression. The Caspian sea which seems to have encountered a similar phenomena except for the last reconnection, presents all the coastal regions of Mazandaran and Gilan (Iran) sand dunes as high as 20 m made of sandy particles and fragments of shells and being parallel to the seashore. As for the relict Black Sea dunes, these dunes are occasionally cut across by wind blows.

As in the Caspian Sea (Kvasov, 1975; Svitoch *et al.*, 2000), the Black Sea water level fluctuations appear to be directly linked to climate variability. These enclosed basin (when not connected to the Mediterranean for the Black Sea) has reacted almost by reaching highstand and outflow in cold periods and lowstand through evaporation in warm periods. When the Mediterranean penetrated through the Dardanelles Strait ca 12,000 y BP, the Marmara Sea was caught in a state below its outlet (Aksu *et al.,* 2002a; Aksu *et al.*, 1999).

Whether catastrophic flooding is hydraulically possible is an additional open question. Using a hydraulic model for the events following the connection of the Black Sea to the Mediterranean and assuming that the sill cross-section has remained more-or-less unchanged, Lane-Serff *et al.*, (1997) showed that significant freshwater outflow from the Black Sea occurred only 500-1,000 years after the Mediterranean sea level reached the Bosphorus sill depth when a two-layer exchange between the two seas became established, because there is an upper limit to the water flux that could pass through the sill. This delay corresponds in order of magnitude to the lag between the onset of sapropel deposition in the Mediterranean and the Black Sea. Furthermore, Lane-Serff *et al.* (1997) demonstrated that it took 2,500-3,500 years for the bulk of the freshwater in the Black Sea to be replaced by salty Mediterranean waters and for euryhaline-marine conditions to be established. This period corresponds to the time of sapropel deposition in the eastern Mediterranean.

Whether or not this reconnection was catastrophic, the isue is about the consequences of a flood on the Neolithic population. The archaeological bases presented by Ryan and Pitman (1999) are predicated on a huge archaeological assumption, namely that after the beginnings of agriculture the ancient Near East suffered a drought forcing the first farmers to find refuge in a more friendly climate, on the pre-flood Black Sea coast. A more realistic picture of the Neolithic Diaspora in Europe may consider it to have been a mixture of various waves, currents, and eddies of people, animals, and plants. In some areas, an influx of migrating farmers swept with it any sparse local foraging populations as it deposited its own agricultural communities. Elsewhere, early farming communities appeared as isolated pioneer outposts in a multicultural landscape of foragers and farmers. The debate is still ongoing about the role of catastrophic events on population movement.

Geochronology and Myth – are Gods Catastrophes ?

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"Man is certainly crazy; he could not make a mite, but he makes gods by the dozen." (Michel de Montaigne)

The power of speech emerged from a spandrel, and made it possible for information to pass from one generation to another. Art and writing reinforce this process, prevent the downgrading of information, and perpetuate it as myth. Some myths may encode catastrophic events in history as deities, and contain internal evidence of their chronology. The evidence of geology may allow us to construct an absolute time scalefor myths.

INTRODUCTION

It is said that a Harley Street psychiatrist can live very well on the fees of a mere twelve patients a year. Consultations with the Oracle of the Dead, organized by the Sibyl of Cumae in Baia near Naples were also expensive. Odysseus and Aeneas were amongst the famous who could afford such luxuries. The supplicant first had to pay for the sacrifice, i.e., in Aeneas' case, the roasting of seven bullocks and seven ewes, as well as the olive oil with which they were basted, and the wine, barley bread, and other accompaniments, these for the Sibyl herself. Further expenses were due to the priests and assistants who conducted the ceremonies. After exposure to a sophisticated blend of psychological preparation which included sensory deprivation and consumption of psychedelic drugs, the victim was conducted to the Underworld. A child's first communion is far less harrowing, but is perhaps a dilute echo of similar principles. Most people reading Virgil's *Aeneid* imagine it as myth or allegory. *But it really happened*! "What is not widely appreciated is that these episodes were based on an actual physical location" wrote Temple (1984), who summarizes the archaeological evidence, and explains in detail how the fraud was stage-managed*. How the architects at Cumae were able to construct this underworld, apparently without any exploratory boreholes, remains unknown, but detailed geological knowledge of the site including its subterranean rivers and groundwater dynamics was clearly an essential prerequisite. Could ancient dowsers have been involved ?

Much else once believed mythical has subsequently revealed a factual basis. Herodotus' mythical Scythians, fearsome horsemen of the steppes, were identified by Gordon Childe with the "corded ware" culture and as proto-Indoeuropeans, with Kurgan culture by Marija Gimbutas (Renfrew 1987). It was the *Iliad* that inspired Schliemann's search for Troy. But we should not

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* Another entrance to the Underworld has been described in northwest Greece (Fouache and Quentin, 1996).

fall into the trap of positing a naturalistic explanation for all the details of mythology. "We need not try to make history out of legend, but we ought to assume that beneath much that is artificial or incredible there lurks something of fact." (Woolley, 1934). Here I examine some places where facts are thought to lurk, i) in the armories of battling deities, and ii) in the waters of flood myths.

Chronology is the vertebral column of the earth sciences, as it is of all disciplines which seek to understand historical and evolutionary processes. Mythology too contains internal evidence of chronology analogous to that which can be obtained from analysis of stratigraphic sequences. The Fall precedes the Deluge. Odin succeeds Ymir. *Et sic deinceps*. Genealogies inform us that Gaia follows Chaos and precedes Tartarus, Uranus, and Pontus ; the Titans and Cyclopes, Erebus and Hemera, Aether and Eros, and the Hecatoncheires were contemporaries of Uranus' generation. We can represent this succession in the same way as a geological section with Chaos near the bottom. Deeper still, we can see the Goddess identified by Cauvin as the first deity (see below). There is an unconformity between Her and Chaos; Her origin must be sought in an earlier cultural age. She is in fact a different kind of deity from those in overlying layers, since She (accompanied by the Bull) has pierced the latter in the manner of a magmatic dyke, left metamorphic remains in the younger strata, and enriched the mythological landscape. She is also distinguished from later deities in that her origin seems to have been biological and astronomical (in cyclical time) rather than catastrophic.

i) The weapons which allowed Zeus and the Olympians to overcome Kronos and his allies, leading to the succession of one generation of gods by another, may encode volcanic phenomena, and specifically the great eruption of Thera in the 17th century BC (Greene, 1992). In his foreword to *Centuries of Darkness* (James, 1992), Colin Renfrew identifies the dating of the Thera eruption as one of the two key issues in archaeological chronology (the other is the dating of megalithic monuments in northwest Europe). In the present context, we can also see that it is a key issue in any attempt to construct an absolute chronology for geomythology. The identification of this eruption as the source of Hesiod's *Theogony* is therefore reviewed, as well as the dating problems associated with it.

ii) Presently very topical is the hypothesis that the site of the flood recorded in *Gilgamesh*, *Genesis*, and elswhere is the Black Sea basin. Even if such a flood took place (see Lericollais, this volume), and there is substantial evidence (e.g., Aksu *et al.*, 2002) that it did not do so in the way described by Ryan and Pitman (1998), it is pertinent to examine other floods known to geologists as putative sources of flood myths.

MOTT GREENE'S GEOMYTH

The great eruption of Thera, now Santorini, in the Aegean Arc has been linked to the collapse of Minoan civilization in the late Bronze Age, to the Biblical *Exodus*, and to the destruction of Plato's *Atlantis*. Hesiod's *Theogony* provides a genealogy of Greek gods and godesses and of their power struggles. The drama has a varied cast. *Kyklopen*, means circle- or round-eyed, and these creatures were sons of earth (Gaia) and sky (Uranus). In the *Theogony*, Hesiod has them with a single eye in the middles of their brows. They helped Proitos build the "cyclopean walls" of Tiryns and Mycenae, were the earliest inhabitants of Sicily, and worked at the forge of Hephaestos under Mount Etna. The scholiasts identify three kinds: Hesiod's "Thunder" and "Lightning", weapons of Zeus; the wall builders, *gastrocheires* or *cheirogastores*, whose hands emerge from their bellies; the giant Polyphemus of the *Odyssey*. Greene (1992) wrote: "When I read that a Mediterranean tradition contains figures... who are like gods... mighty unpredictable giants who live in high peaks in hollow caves from which they issue forth with sporadic violence... that they gave invisibility to Pluto and gave Poseidon the trident that shakes the sea; and that they are associated with fire demons, I think about volcanoes." He then suggests that the variety of *kyklopen* form a classification "of a diverse but related series of natural phenomena", and illustrates it with examples such as the "contrast between the peaceful solfataric activity of the *Campi Phlegrei* and the brooding unpredictability and menace of Vesuvius ...". As mentioned below, the *Campi* are not always as peaceful as Greene implies.

Mediaeval sources offer parallels; the *mons igneus* and *mons fumosus* of St Brendan's *Navigatio* may refer to Hekla in Iceland, and the 'bursting forth' of loughs in *Leabhar Gabbala* to local floods. Similarly, when biologists read in *immrami* of stinging creatures the size of frogs

infesting oar blades, and worms which eat through the outer hides of a curragh, they must think of jelly fish and the shipworm *Teredo*. The absence of classificatory systems into which such observations could have been placed by witnesses from earlier traditions does not prevent us from recognizing them as items in our own systems.

The *Theogony* is very old, and some parts are of Hittite and Hurrian origin, a thousand years older than Hesiod's Greek, and thus a thousand years nearer in time to the eruption of Thera (the fifth tablet of Gilgamesh dreams of a darkened earth, loud roarings, and flames, and the earliest known representation of an eruption, of Hasandag, was found at Çatal Hüyük, dated about 8000 BP). This is now recognized as a common (universal ?) feature of ancient literature, that natural knowledge existed side by side with myths and theogonies, and that both draw on roots deep in the preclassical period (Burckert, 1998; West, 1997). This raises two important points, i) about the routes by which eye witness accounts of an event were transmitted to the present day, and the corollary of how accurate these processes are, and ii) what cocktails of fact and poetic inspiration have reached us.

i) If Greene is correct in his reading, the thousand years of transmission between the Hittite account of Thera's eruption and Hesiod's version in the *Theogony* led to little distortion, since in his opinion the unique signature of the volcano is still recognizable. If the transmission was oral, there must have been something very special about the event – that it acquired sacred meaning (Wyatt, 2001), or became 'fossilized' by persistent anthropomorphic and animistic icons - to ensure that the details were accurately preserved from generation to generation. Greene does not consider the possibility that the *Theogony* may encapsulate an earlier eruption of Thera, i.e., that of Cape Riva, dated to about 21,000 ka by radiocarbon or an eruption of some other volcano in the Aegean arc whose signature may be similar enough to Hesiod's chronology of events. But he does see that some of the weapons can refer to volcanic activity elsewhere in the Mediterranean, especially that of Etna.

The Welsh antiquary Edward Lhuyd interviewed one Cormac O'Neill in 1927, and was retold the legend of Elkmar's expulsion from Bru na Boinne (Wooding, 2000); I don't know the history of the punishment of being cast adrift, but I suppose it went out of fashion quite a while before 1927. Much longer transmissions are possible by means of art/ritual. Archaeoastronomer Luz Antequera Congregado traces the Palaeolithic bull/man with lance/bird on stick theme from Lascaux via the tomb of Senmut (reign of Hatshepsut) and a Roman temple at Dendera (Egypt) to the nineteenth century (Bode, *Les Étoiles et les Curiosités du Ciel*, 1882). The first link in this chain lasted more than 10 000 years. What happens to oral transmission as stories pass from one language to another, and one by one the languages themselves become extinct? Old Irish *immrá* means to row about, and *immrama* are mythological voyages in search of the "Otherworld". They were written down by monks in the 7th and 8th centuries, garbled, bowdlerized, censured, but certainly contain earlier material, some of it prechristian. In an 8th century compilation, the hero Maelduin visits a variety of islands in which we can perhaps recognize seals, walruses, and great auks, as well as phenomena like sea ice. Thorfinn Karlsfin (in the same year that Leif Ericsson was there, 1010 AD?) was told by Esquimos on the Labrador coast of Hvitrmannland, that a settlement of white men and Irish anchorites, *papars*, preceded the Norse in Iceland by 80 years. What we now call the Irminger Sea between Greenland and Iceland is labelled on at least one old map the Irish Sea, and Mercator's famous 1538 map distinguishes the Labrador Sea as *Oceannus Deu calidonius*. Several examples of oral tradition perpetuating genealogies and myths over long periods (centuries, millennia) are collected by Collina-Girard (2002).

ii) It is now widely accepted that myths mix history and legend. We might perhaps analyse specific myths to discover the principles of the blending process, and construct analogies of Shepherd's diagrams to represent the cocktails which we have (Fig.1). For one axis of such a diagram, we might select a line between natural (external) phenomena, such as astronomical cycles and catastrophic and uniformitarian geological processes on the one hand (apex 1), and psychological (internal) imperatives like Jungian archetypes on the other (apex 2). From these two extremes, we could draw two further axes meeting to form the third apex (3) of a triangle, which can be labelled « ideology ». The ideological apex is the focus of the reworking of myths which has taken place with the aim of providing blueprints for social control; the Priestly school's adap-

Fig.1. Diagram to illustrate how the composition of myths which may encode natural phenomena can become modified by psychological and ideological forces. Two examples are shown, the Great Goddess who dominated Palaeolithic myths and was later converted to a mere consort of a god, and the "universal flood" of many cultures later edited by the Priestly School to foster Old Testament patriarchy.

tation of the Babylonian and Canaanite myths embedded in *Genesis* is a well-studied example, the downgrading of the Mother Goddess mentioned later is another. In the biblical story, Cain is the bad guy who wins; this myth is sometimes seen to encapsulate the conflict between agriculturalists and pastoralists, and perhaps encodes the new demographic pressure of the emergent Neolithic. But in a Sumerian version of the same story, the roles of the two brothers are reversed, and then we might interpret it as an ideological response to increasing aridity (witness the Assyrian kings who lived in tents, or the contemporaneous collapse of Egyptian Old Kingdom, both about 2200-1900 BC). Ideologies change in response to natural forcings; memes evolve.

Mott Greene's detailed analysis of the battle sequences "leaves no doubt that the phenomena described are volcanic eruptions. Not only that, but eruptions described so carefully and in such detail that the volcanoes in question can be identified and the particular eruptions of the volcanoes dated. The battle of Zeus and the Titans recounts the eruption of Thera, in the Aegean arc..." ? Here is Greene's comparison of Hesiod's lines with the volcanic signature of Thera identified by geologists:

	Hesiod	Thera
1	a long war	premonitory seismicity
2	both sides gather strength	increased activity
3	terrible echoes over sea	first phase explosions
4	ground rumbles loudly	tectonic earthquakes
5	sky shakes and groans	air shock waves
6	Mt. Olympus trembles	great earthquakes
7	steady vibrations of ground	earthquakes
8	weapons whistle through air	pyroclastic ejecta
9	loud battle cries	explosive reports
10	Zeus arrives; lightning, thunder, fields and forests burn	volcanic lightning, heat of ignimbrites
11	Earth and sea boil	magma chamber breach
12	immense flame and heat	phreatomagmatic explosion
13	sound of earth/sky collapse	sound of explosion
14	dust, lightning, thunder, wind	final ash eruption
15	Titans buried under missiles	collapsed debris

The tsunami generated by the collapse of the caldera could have been 50 m high. Cita *et al.* (1997) link deposits up to 20 m thick on the Sirte Abyssal Plain to this tsunami. But there is no tsunami in Hesiod's cast.

The story of the fabled island-continent of Atlantis has come down to us from the dialogues of Plato, the *Timaeus* and *Critias*. Serious scholars sometimes interpret the story as a literary

device, or dismiss it as a folk tale. Others, although a literal reading of the details given by Plato does not warrant it, have suggested that Atlantis was in fact Santorini or Crete, and that the destruction of Atlantis "in a single day and night" was due to the great eruption. Akrotiri was buried by the eruption, but unlike the victims of Vesuvius at Pompeii, its inhabitants had sufficient warning to escape – they may have fled by sea – with their movable belongings. A unique feature of the myth of Atlantis is that Plato is our only source, so that it post-dates the time when all other myths considered here were formed (see below); it has a different "body plan", and we can perhaps recognize a non-conformity additional to that between the Great Goddess and Chaos (Fig. 2).

The pre-Greek or proto-Greek Late Bronze Age civilization of Crete was named *Minoan* by the British archaeologist Sir Arthur Evans, since he associated Knossos with the legendary King Minos. This culture reached its peak in the 17th century BC, and its strength was based on sea
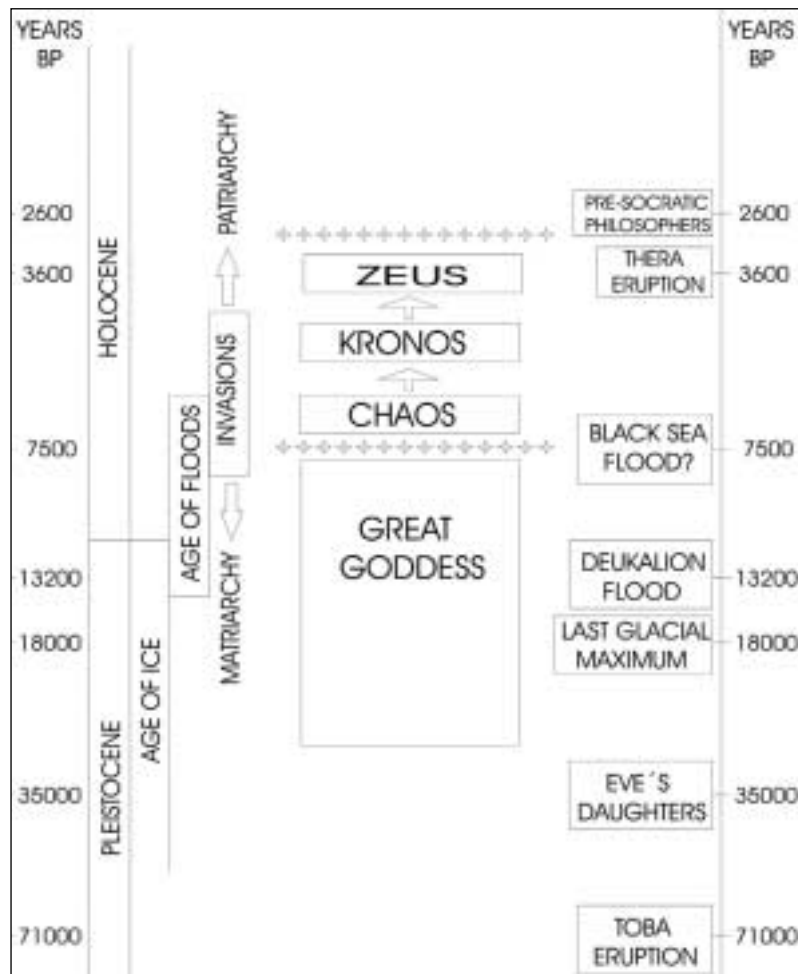

Fig. 2. Tentative sketch of mythological timeline represented (centre column) as geological section; note time scale is logarithmic.

Two nonconformities are indicated, between the Great Goddess and Chaos, and above Zeus; Plato's *Atlantis* is younger than the second nonconformity, and here considered to be a distinct form of myth. The right hand column shows some catastrophic events which may have influenced the evolution of myths. Sakellariou's and Ryan's floods are considered elsewhere in this volume (by Sakellariou and Lericollais respectively); Tchepalyga's flood, a glacial outburst from northern Eurasia, was described at a recent meeting of the Geological Society of America (Seattle, November 2-5, 2003 http://gsa.confex.com/gsa/2003AM/finalprogram/abstract_63243.htm). These floods are named for their authors, since there is so far no general agreement which of several candidates (Ryan's, Tchepalyga's, and others in Mesopotamia, the Persian Gulf, and even as far away as the Sunda Sea) might have inspired the Gilgamesh/Noah myth. Also indicated are the Toba eruption which may have extinguished mid-Pleistocene myths by fragmenting any then existing "small world" of cultural transmission, Eve's daughters whose descendants now people Europe, and the pre-Socratics philosophers to whom we can trace post-mythical models of nature. The invasions which bridge the trend from matriarchy to patriarchy are those of genes and memes, not necessarily marauding hordes.

power. The decline of its power has been attributed to the loss of its navy, caused by the Thera tsunami (?), and the vacuum left by this decline has been used to explain the rise of the Iron Age Dorians and the shift of the centre of power to the Greek mainland.

Several details of the biblical account of the plagues of Egypt and the Israelis' subsequent flight suggest volcanic events; darkness over the land for three days, a pillar of cloud by day and a pillar of fire by night, and the opening of the waters (Pomerance, 1970). The darkness would then be due to the dust veil, the pillar the plinian column - but out of sight over the horizon from Lower Egypt, and leading the Israelis in the wrong direction too! - and the opening of the waters caused by the tsunami (Bernal, 1991). There is evidence that the tsunami from Thera reached Levantine coasts (Stanley and Sheng, 1986), so it must have reached the lower delta too.

DATING THE THERA ERUPTION

The accompanying table summarizes the main efforts to date the Thera eruption, taken mainly from Bernal's (1991) account. Bernal concludes that "the scholarly consensus in favour of the 15th century collapsed in 1987". As the table indicates, this collapse was mainly due to the acceptance of dating techniques additional to those of traditional archaeology.

AD	authors	evidence	BC
1939	Spyridon Marinatos		1450
1960s	Akrotiri excavations	LM IA pottery or earlier, so before 1500	16th century
1970s	Leon Pomerance	Exodus linked to Ramses ; no 'break' in Egyptian records in 15th century	13-12th century
1970s	Philip Betancourt	Radiocarbon (olive stones)	17th century
1970s	Valmore LaMarche	Dendrochronology ; no large Krakatoa effect in 15-14th centuries	1628
1979	Peter Warren	Redate of LM IA following comparison with Levantine pottery	1600
1980	Barry Kemp, Robert Merrillees	Egyptian/Aegean radiocarbon synchronies	1600/1575 'or even earlier'
1980	M. Marthari	Pottery from Thera destruction with Middle Helladic (ended 1600) features	17th century
1980	Hammer *et al.*	Ice cores	1390
1985	Michael Baillie	Krakatoa effect in Irish bog oak	1628
1984-87	Kevin Pang, Hung-hsieng Chou	Bamboo Annals etc ; end of Xia Dynasty	1625
1987	Hammer *et al.*	retraction	1644

Since 1987, further evidence from tree rings in favour of the 1620s has been published, but tephra from Greenland ice cores for this decade seems not to be from Thera (unpublished rumours !), and an earlier date (1645-1647) like that of Hammer may be proposed (I am indebted to Floyd McCoy, pers. comm., for this information). Thus one possible anchor for an absolute time-scale for mythology is 1645-7 BC.

CATASTROPHIC FLOODS

Flood myths are found nearly everywhere, and we are familiar with catastrophic floods episodically in our own time due to exceptional rainfall, storm surges, tsunamis. Some future scenarios due to global warming include severe risks of flooding in many regions. It is probably reasonable to assume that if any or all of these myths contain folk memories of real events, then the floods which inspired them occurred after the last glacial maximum (LGM). Two mythical floods have dominated the imagination of *western* man, that of Plato's Atlantis, and that of Noah from *Genesis*, the former marine, the latter nominally due to forty days of rain. There have been other dramatic floods since the LGM, but for many of them knowledge is largely confined to specialists. Examples are those following the breaching of proglacial lakes in northern Eurasia, which

led to high stands of the Aral and Caspian Seas, the latter perhaps 50 m above its present level (Mangerud *et al.*, 2001). The 4th century Roman historian Ammianus Marcellinus (in *Res Gestae*, citing the 1st century BC scholar Timagenes) described the Gauls as partly autochthonous and partly immigrant from land and islands beyond the Rhine, driven from their homes by wars and the flooding of the tempestuous sea; this may mean from areas now submerged in the North Sea, which we know has episodically expanded in recent millennia at the expense of the surrounding lands (e.g., Gram-Jensen, 1985). The English Channel and Celtic shelf may have been flooded catastrophically by the breaching of the land link between the hills of Artois and the North Downs in England (Smith, 1985).

Flooding due to the evacuation of proglacial lakes is now known to have been a frequent and widespread phenomenon. Catastrophic flooding from the intermontane depressions of the Altai-Sayany mountains and regions farther east in northern Eurasia have been described by Rudoy and his colleagues. Flow rates following ruptures of the ice-dams are estimated to have been 30 or more times greater than during present day thaws, with flow volume exceeding 10^6 m^3/s. The greatest flow power was determined for a Chuya-Kurai floodstream (about 13 thousand years ago) ; its volume was more than 18 million m^3/s (Grosswald and Rudoy, 1996; Rudoy, 2002).

New World floods seem a more likely source of flood myths there, and some of them were so massive that they must have affected the Old World too. Among the largest catastrophic outbursts of fresh water from Lake Agassiz into the North Atlantic Ocean were those at 10,900 ^{14}C yr BP (9500 km^3), 10,100 ^{14}C yr BP, (9300 km^3), and 7700 ^{14}C yr BP (163,000 km^3). These outbursts coincide with the start of the Younger Dryas, Preboreal Oscillation, and 8.2 ka cal yr event, suggesting that outbursts from Lake Agassiz may have repeatedly influenced hemispheric climate by affecting ocean circulation and North Atlantic Deep Water production (Teller *et al.*, 2002). The flow at 8.2 ka is 5-12 Sv, equivalent to a major ocean current. "Although none of these short outbursts of Lake Agassiz waters to the oceans resulted in sea level rises of more than 0.5 m, some caused rapid transgressions of the ocean across shallow continental shelves and marine basins. For example, the 163,000 km^3 outburst from Lake Agassiz at 8400 yrs BP would have caused an abrupt marine transgression of 0.7 km in one year across the floor of a gentle continental shelf with a slope of 1 in 1500, like that of the Mississippi River delta. On the nearly flat floor of the Persian Gulf (1:25,000 slope), which was dry during the last glacial maximum, the final outburst from Lake Agassiz would have resulted in a transgression of 12 km in only a year. Thus, in the Persian Gulf basin, not only did melting ice sheets produce a continuing ocean transgression of 140 m every year for 7000 years, but there was also an abrupt transgressive flood of 12 km about 8400 years ago." (Teller *et al.*, 2002). A permanent rise in sea level of 0.5 m must of course be catastrophic for low-lying coastal areas, but even temporary rises of that magnitude may be devastating, a realization which has led contemporary man to make enormous investments in barriers against storm surges.

The Tamils have a tradition that their poets' academy or Sangam existed for ten thousand years, and that its seat (along with the entire Tamil capital) had to be moved thrice because of the rising sea level. They also believe that their country once stretched far to the south, including Sri Lanka and the Maldives, a lost Tamil continent called Kumarikhandam.

The mean rise in sea level since the Last Glacial Maximum is estimated at about 100-120 m. This rise was not monotonic as is sometime assumed, and as the example of Lake Agassiz illustrates, and the evolution of continental shelves is not simply a matter of slow encroachment of the sea, even if processes on longer time scales like isostatic crustal uplift are ignored. The appropriate models are fractal, as the annual Nile floods illustrate, and as Holocene climate changes show. When the Younger Dryas ended and the Neolithic began, there was a 7 degree rise in global mean temperature in a decade.

HOW FAR BACK IN TIME SHOULD WE LOOK?

Studies of single nucleotide polymorphisms (SNPs) suggest that "Mitochondrial Eve" lived 150,000 to 200,000 years ago during the Riss glaciation, and her descendants moved out of Africa 100,000 years ago when the 'Weak Garden of Eden' model starts to run (Harpending *et al.*, 1998). Choice of the names Eve and Eden provides ammunition for deconstructivists ! There

may have been a population bottleneck - some estimates (Jones and Rouhani, 1986) suggest there were less than 10,000 breeding adults about 70,000 years ago following the eruption of Toba in Sumatra (Ambrose, 1998). This eruption may have accelerated the cooling which preceded the Last Glacial Maximum. Some American geologists think that another cataclysm of this magnitude is overdue, centred this time on the Yellowstone National Park in North America. We can perhaps assume that most ancient knowledge accumulated prior to the Toba bottleneck was lost as the "small world" (Watts and Strogatz, 1998) of mankind would have fragmented into isolated groups. The slate was wiped clean. This period was followed by the "Great Leap Forward" (Diamond, 1991) which we know as the Upper Palaeolithic ; the human population expanded exponentially (Harpending et al 1998), possibly by virtue of its new tools, art, and mutations of the *FOXP2* gene which may have allowed advanced language skills to be acquired. "The Seven Daughters of Eve" (Sykes, 2001) lived about 40,000 years ago (?) in Europe ; this was about the time of the ultra-Plinian eruption of the *Campi Flegrei* caldera (Fedele *et al.*, 2003). Was there another more localized bottleneck ? Another cleaning of the slate ? The Biblical flood drowned the whole seed of Adam except Noah and his three sons, who were subsequently to repopulate Asia (Shem), Africa (Ham), and Europe (Japhet). Does this myth contain a lingering memory of a population bottleneck ? Or is it just the surviving skeleton of one of the doubtless innumerable mythologies once current among a welter of Neolithic and Bronze Age tribes, most of which have passed irrevocably into oblivion ? Geology enters questions about human expansion in another way too, since mountain ranges, deserts, and water constrain migration routes; these constraints must also modulate the architecture of the smal worlds in which myths evolve.

Jacques Cauvin (2000) argues that there was a mental revolution in the Upper Palaeolithic which created a chasm between man and the divine, and built a bridge from animism to religion; he claims two deities emerged from this revolution, a universal goddess (Great Mother, the White Goddess of Robert Graves) and a bull god, perhaps her totem. Other gods might have been inspired by destructive earthquakes and volcanic eruptions, and their sequelae such as tsunamis, and younger ones by the events, some of them also catastrophic, floods prominent amongst them, which ushered in the Holocene. Cave paintings and other artefacts were already highly developed by 30,000 years ago. This period then is the earliest from which we could expect to find cultural records of geological events. Expert opinion so far however seems to be very varied about the significance of the paintings of Lascaux and other Palaeolithic sites. They may reveal more interest in zoology and astronomy than in geology. Mithen (2003) calls Palaeolithic art "the equivalent of our CD-ROMs today", and writes "The art, the mythology and the religious ritual served to maintain the constant acquisition and flow of information".

But astronomy is the origin of the cardinal points, and must underpin topographical knowledge, an essential tool of the earth sciences. The bull or aurochs is a central character of this art, whose horns may have been seen as lunar crescents, and whose bucrania are said to recall the human uterus and fallopian tubes, and thus to have symbolized regeneration (Gimbutas, 1989). It cannot have escaped the attention of Palaeolithic observers that the human menstrual cycle has a period of one synodic month, that gestation lasts nine synodic months, and that the reproductive and migratory patterns of their food resources were synchronized with lunar phase. The shaman who knew his stuff could guide his tribe to the salmon run at the proper time. Astronomical cycles were a practical concern. Will Durant wrote somewhere that "Civilizations exist by geological consent, subject to change without notice". We could say that they also exist by celestial consent, and that the astronomical future is easier to predict than the geological. Some of the relevent astronomy might be catastrophic too, like the geology. The Underworld (a geological realm) begins in the constellation of Cancer.

According to some scholars** , when Indo-European speakers came, they changed all this. Goddesses which had formerly been created by parthenogenesis were now born of gods, like Athena from the head of Zeus, Aphrodite from the blood spilt when Kronos castrated his father Uranus, Eve from Adam's rib; farcical, really, dirty minded even. The bull became a bully, and raped Europa. It was patriarchal societies (Semitic and Indo-European) which created the Old

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** Mother goddesses are not universally accepted as the dominant deities of Palaeolithic times.

Testament and the Iliad: "The death throes of the Great Mother can be read between the lines of these sexist credos" (Schlain, 1998). But She lives on, mutilated perhaps; a modern descendent, the Virgin Mary, is still the most popular member of the Roman Catholic pantheon. We need to bear in mind that ideological impositions may distort astronomical and geological signals hiding in deities' personalities. But all this is much later. On balance, it looks probable that the mythological big bang occurred in the late Pleistocene and early Holocene when so many events of a catastrophic nature took place.

Alberto Porlan (1998) argues that toponomy preserves a pre-Indo-European systematization of topography, and while we cannot yet read it, might in the long run allow us to recognize a route from Palaeolithic geognosy to that of the literate cultures of Preclassical and Classical times. Porlan relates topography to the names of gods; this intertwining of natural knowledge with mythology still persists, and one challenge here is to unravel the natural from the mythic. Mythologists have identified several potential origins of their subject matter. Bulfinch (1855) for example listed scriptural, historical, allegorical and physical sources, with fire, water and other natural forces becoming personified as deities. Astronomy then provides the empirical basis of chronology and calendars, the key reference points for topography, and the names of deities. So while attention is directed here to fire and water, more specifically to volcanic eruptions and floods, we should not forget the background of celestial mechanics.

SPATIO-TEMPORAL SCALES

The volcanic winter which may have followed the Toba eruption could have lasted for decades or centuries, which must make us pause to consider the distinction between long term, progressive trends and "instantaneous" catastrophic events. Marine shells at high altitudes, which so provoked classical philosophers, might have reached there either by uniformitarian or catastrophic processes. Mountain building and major slumps like the tsunami generated by the Storegga slide have very different time scales, but both can place marine shells well above sealevel. The distinction of course is arbitrary, and depends partly on the time filter used, but also on the magnitude of catastrophic events, and how long ago they took place. The greater the magnitude of a catastrophe, the more likely it is that there will be long lasting progressive trend of some kind following it; given events of similar magnitude, those farther back in time are more likely to be classified as 'instantaneous' since the records available from which they can be identified are increasingly compressed or eroded. These expectations can often be encapsulated in power laws such as those used to describe the statistics of earthquakes or volcanic eruptions. But on the time scales of interest here, much progress is being made in the analysis of such records as deep sea cores and ice cores, and some records such as tree rings and varves now allow us to probe deep into the early Holocene and beyond with annual (or better) resolution.

Time scale considerations enter our equations from the historical perspective too. Rackham and Moody (1996) write that "The famous eruption of Santorini, once thought to have caused the collapse of Minoan civilization, is now known to have been a least a century too early; it probably had only minor effects on Crete". This statement is presumably based on the now somewhat out-dated view that the Minoan collapse was an overnight affair. It is natural to assume that major volcanic explosions, earthquakes, etc., cause instant destruction, as they may do to the hardware, the cities and canals; the software, society, may decay more slowly, or the opportunities which disaster offers to rivals may not be exploited at once. Social changes exhibit viscosity. When drought struck the Old Kingdom in Egypt towards the end of the third millenium (see above), there was a progressive reversion from agriculture to nomadism, and persistent migrations to the delta region, which led to perhaps three centuries of social unrest. This was coincident with the fall of Akkadian culture in Mesopotamia, where there is an occupation hiatus lasting from about 2200 to 1900 BC. There are earlier parallels to the end of the Old Kingdom, such as that from Early to Late Natufian coincident with the shift from the last Interstadial of the Pleistocene to the Younger Dryas, triggered by the collapse of the North American ice sheet around 12, 800 BP (Petit-Maire, this volume, provides more details).

Spatial scales are part of the historical perspective too, and our new appreciation of "small worlds" and "six degrees of separation" come to mind again when we consider cultural trans-

mission, whether oral or written. The tragedies of Aeschylus or Sophocles may enact themselves within the back-scratching and back-biting elites of small city states, but *Oresteia* is about home-comings, and *King Oedipus* ends in exile. It is the weak links which these movements imply which make the world small. West (1997) discusses the problem, and believes the flow from the Middle and Near East to Greece was especially strong in the periods 1450-1200 BC and in the 8th and 7th centuries, and concludes that the transmission of poetry was mainly oral but constrained by textual versions. For some texts such as Gilgamesh, the geographical spread of copies, fragmentary now, is remarkably widespread (West's figure on p. 591). He also stresses the role of bilingual poets, the divergences which could stem from different rescensions, and the parts of the process we cannot see due to the poor survival of material in some languages (eg Aramaic, Phoenician). As an example, West sees direct links between 7th century Assyrian court literature on the one hand, and Hittite necromantic rituals on the other, with the *Iliad*, only one degree of separation away in each case. This is an indication of how large the spatial scales of these links are; the corresponding time scales are of the order of millennia. West's oral/textual conclusion may be adequate for the period since writing existed, but if oral transmission alone is effective over *really* long periods, then we would still like to know how long, since the power of speech is plausibly older than *Homo sapiens*, at least if anatomy is our guide. (It has been claimed that the form of the hyoid arch and the size of the anterior condylar foramen through which the hypoglossal nerve exits the skull are consistent with Neanderthal speech (Kay *et al.*, 1998), though this is denied by DeGusta *et al.* (1999) ; perhaps the *FOXP2* gene is needed to complement the appropriate anatomy, and the combination is a Gouldian spandrel***). The end point of these concerns lies in the 6th century BC, when pre-Socratic philosophers of the Milesian School laid the foundations of Lyell's and Darwin's uniformitarian views.

There is of course considerable evidence of sophisticated geological knowledge in classical times, as we can appreciate from reading Book XV of *Metamorphoses*, where processes still recognized by modern geologists emerge from Ovid's Pythagorus (see Lyell, *Principles of Geology*). Aristotle (*Meteorics*) attributed earthquakes to the generation of wind within the earth, and associated them with volcanic phenomena. Strabo (*Geography*) noted both widespread and local sinkings of land, and rises of the seabed; he also suggested that some islands were born of volcanism, and that others were torn from the mainland by earthquakes. He was aware of the growth of deltas, and their control by tidal currents. Seneca (*Quaestiones Naturales*), based on eyewitness accounts of an earthquake in Naples distinguished the up and down motion (*succussio*), the oscillatory motion (*inclinatio*), and perhaps also the vibration. Aristotle saw that first marsh and then dry land was created by alluvial deposits and gave examples from the Black Sea, where ships had had to reduce their draughts in the sixty years preceding his account. Xenophanes of Colophon (614 BC), Xanthus of Lydia (464 BC), and others inferred from marine shells among mountains that the land had risen from the sea. Herodotus, Eratosthenes, Strato and Strabo noted the vast quantities of fossil shells in different parts of Egypt, together with beds of salt, as evidence that the sea had once spread over the land. This knowledge and these models belong to modern times, while the mythical events which may contain memories of geological catastrophes do not. Some of these processes are examined elsewhere in this volume: Andreas Vött and Helmut Brückner describe coastal changes due to progradation and other processes in the Acheloos delta (Greece) and in Aegean Turkey respectively, and Pablo Silva traces the impact of earthquakes and tectonics on coastal morphology in southwest Spain. The time period of interest here is then the millennia preceding Hesiod, and corresponds to the last phase of human expansion, from the Palaeolithic through the Bronze Age and early Iron Age.

Ancient (Ugaritic, Assyrian, Egyptian, Semitic,...), classical (Greek, Roman), and Mediaeval (Sagas,...) sources contain various categories of pre-scientific information. On the one hand, we recognize that descriptions of nature and theories about how it should be classified are precursors of present day science. Data recorded millennia ago can still play constraining roles in some research fields (Babylonian eclipses, Nile floods, volcanic eruptions, etc.). On the theoretical side, we can, if we wish, trace the roots of Mendeleev's periodic table back to Aristotle's earth,

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*** Parts of the cerebral cortex would also have needed to be reorganized somehow !

air, fire, and water, the origins of atomic theory to Democritus, notions on the causes of earthquakes to Seneca, and the landbuilding power of sedimentary processes to Herodotus and Strabo. "Egypt is the gift of the river" wrote Herodotus (and mighty changes are underway today since the Nile was "tamed" at Aswan – anthropogenic impacts on geological processes are discussed by Brückner, this volume). But on the other hand, these sources also contain much more elusive records of events which are traditionally claimed by mythologists and others, and which are not generally considered to be of much interest to natural scientists.

WHAT PROCEDURES SHOULD WE ADOPT IN GEOMYTHOLOGY?

So, should we inspect the ancient gods for signs of their putative geological components, or should we look in the geological record for catastrophes which have been tranformed into gods? As we have seen, Mott Greene (1992) chooses the former course in his analysis of Hesiod's *Theogony* where he identifies the signature of Thera's eruption, but it is more usual to search geological records for evidence that myths are founded on real events, as Ryan and Pitman (1998) do for the biblical deluge. One problem with the latter approach is that *any* evidence of a major flood is likely to be ascribed by students steeped in western traditions to that in *Genesis*. Ruggles' (1999) critique of Alexander Thom's megalithic calendars identifies a parallel problem; if, for example, it is maintained that Le Grand Menhir Brisé (near Carnac) is a foresight for observing standstills of the moon, then backsights can almost certainly be identified (and were !), but their functional role within the archaeoastronomical model is far from being demonstrated. Pleistocene and Holocene geological records show that there have been major floods in many parts of the world, and it is highly likely that some have seeded flood myths.

I think the interesting question in the context of this workshop is, can we link geologically identified floods to particular myths or deities? Do flood myths from different cultures have "signatures", analogous to those of volcanic eruptions, which might enable us to identify the kind of flood which inspired the myth? Can we distinguish mythical analogies and homologies as palaeontologists must when they compare vertebrate and arthropod limbs ? Can we separate opaque allusions to Jungian archetypes from external elements, the waters of the womb from the forty days of rain? Georges Dumézil identified what he thought were homologies in Indo-European mythologies, but Claude Lévi-Strauss argued that some of these same features were analogies, parallel but not necessarily generically related. The conflict cannot be easily resolved without a chronology of the structural patterns alluded to.

Many disciplines can help provide answers to such questions. Genetics synthesizes the historical components of its subject matter by constructing trees which summarize lines of descent and trace separate patterns of content to common ancestors; population genetics, as distinct from the kinds of study already mentioned which identify Adam and Eve, gives us anastomosing structures more like fungal hyphae than trees. Historical linguistics follows similar procedures, and also constructs tree-like and reticulate models of phylogeny. In both cases, the phylogenetic signals can be degraded; the genetic signals in modern populations contain elements of the founders, the products of drift and selection and later migrations from the source population, and mixing with other populations from different trees. Some of these signals may vary between analyses based on mtDNA and Y loci if there are sex specific differences in demography. Linguistic analyses face analogous difficulties due to language replacement and hybridization, and the genetic and linguistic maps can be decoupled.

It may be an exaggeration, but it is said there is as much human genetic variation in a single African village as in all the other continents combined. Nevertheless, recent advances in genetics have made possible the separation of closely related ethnic groups, and these to some extent can be mapped onto language groups. Myths too can be mapped onto languages, though again the mapping is very loose. This looseness might be ascribed to several factors, such as the potential existence of universal (Jungian) archetypes, few degrees of separation, and power law distributions of cultural dominance and their changes in time. We can therefore expect there to be a mapping of myths onto geographical genetic patterns. But it may be in many cases that the factors which blur this kind of mapping have already erased any recognizable signals.

SUMMARY

It is suggested that mythogenesis became possible once we became genetically empowered with speech, and that it more or less ended with the pre-Socratic philosophers. All early myths were probably irrevocably lost following a population bottleneck due to the eruption of Toba. Two non-conformities are provisionally identified, between the Great Mother of the late Palaeolithic and the mythogenic big bang of the Neolithic and Bronze Ages, and between the latter and pre-Socratic models. Many myths may have been inspired by geological catastrophes, but have been transformed by psychological and ideological imperatives, notably by patriarchy.