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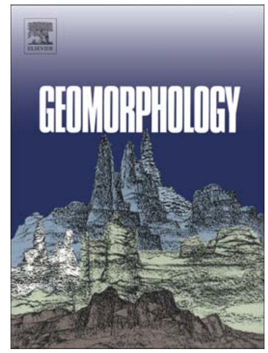

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by

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1. Introduction

In this paper a new chronological framework for the Pleistocene and Holocene geomorphological development of the Algarve is presented. This framework allows the principal Quaternary formations in the Algarve to be defined, permitting a continuous time-constrained account of evolutionary changes to be proposed for the late Pleistocene and Holocene and, to a more limited extent, for earlier episodes within the Pleistocene. Whereas in the Pleistocene and early Holocene geomorphological development was under the control of changing environmental factors, particularly those related to climate and tectonics, from ca. 3000 BP human impact became a significant and increasingly important factor in shaping the landscape – an impact that is possible to monitor through archaeological evidence and, for more recent changes, by means of archival data.

The situation today is in marked contrast to that which obtained just three decades ago when relatively little was known about the Quaternary of southern Portugal. What had been published employed altitudinal correlations with the *classic* interglacial marine levels of the circum-Mediterranean. To the west of Vila do Bispo (Figs. 1 and 2), there is a stepped sequence of erosional surfaces, the upper one of which exceeds 130 m in height. Whereas higher surfaces in the sequence were assumed to be pre-Pleistocene and subaerial on the basis of their altitudes and association with deposits of supposed Pliocene age, lower surfaces were ascribed a marine origin and assigned to the Pleistocene, being correlated with the supposed circum-Mediterranean sequence of interglacial raised shorelines, i.e., 80-90 m - Sicilian I, 50-75 m - Sicilian II, 25-40 m - Tyrrhenian I and 10-15 m - Tyrrhenian II (Zbyszewski, 1958; Oliveira, 1984). Inland surfaces in the Guadiana valley to the north of Vila Real de São António (Fig. 1) were also correlated with putative interglacial marine stages. These deposits, later termed the *Guadiana gravels* by Devereux (1983, pp. 40-45), comprise well-sorted and bedded subangular, crudely imbricated schistose clasts and sub-rounded quartz pebbles with a calibre of 2-7 cm, accompanied by scarce boulders and finer material. They attain a maximum height of ca.49 m above sea level (asl). As a result of the sedimentology of this unit and the fact that it is associated with other large river valleys in southern Portugal (such as the Rio Mira and the Rio Sado both of which enter the Atlantic Ocean to the north of the Algarve) Feio (1946, 1951) argued for a fluvial origin.

The only other lithological unit to be studied extensively was a suite of quartzite-dominated sands and finer sediments, cropping out over much of the central Algarve (Fig. 2). These sands were given a number of names, but by the 1980s the term generally used was the *Areias de Faro Quarteira* or *Faro/Quarteira Formation* (Manuppella *et al*., 1987; Chester and James, 1995). Much disagreement occurred about the age and origin of this formation, with suggested ages ranging from the upper Miocene to the upper Pleistocene (Chester and James, 1995). Putative modes of origin included (i) marine, with some authors correlating the formation with the supposed Tyrrhenian II raised shoreline found to the west of Vila do Bispo (Fig. 1) (Zbyszewski, 1958); (ii) fluvial (Raynal, 1979); and (iii) fluvial with some aeolian characteristics (Devereux, 1983).

By the early 1980s, the reliability of long distance altitudinal correlations in southern Europe came under increasing criticism because of a lack of both dated sediments and continuous morphological features across the region. The Algarve, a region frequently impacted by historic earthquakes including the devastating 1755 *Lisbon* event[1], and was long assumed to have had tectonic activity that was significant throughout the Pleistocene and Holocene, so frustrating correlations based on height and possibly influencing other aspects of landscape development (Chester and James, 1991). It is only in the last two decades that detailed studies of neotectonics using Pleistocene and Holocene stratigraphical and geomorphological markers have been published (see sections 3.3 and 3.4).

From archaeological and historical perspectives, it was known that the Algarve has been continually settled since the late Palaeolithic (Breuil and Zbyszewski, 1946). From the Roman occupation in the second century B.C., the history of the Algarve was reasonably well known (Stanislawski, 1962, 1963; Wuerpel, 1974), although up to the end of the 1970s there was at the time a dearth of studies linking human activity in the Holocene to geomorphological processes and landscape change.

Before the 1980s and away from the coastal zone, geological exposures were few and so frustrated detailed sedimentary study. This has been remedied in the last 30 years as a result of the excavation of thousands of temporary sections by the construction industry, which has turned a formerly rural area into one of southern Europe's principal tourist destinations. More than a decade ago, the present writer and his co-author highlighted two additional issues that frustrated a fully convincing account of the Pleistocene and Holocene evolution of the Algarve being published (Chester and James, 1999, pp. 170-172). First, despite the occurrence of traps for biogenic sediment in estuaries, karstic/structural depressions and at altitude on the Monchique (Fig. 1), no

[1] Estimating the magnitudes of historical earthquakes is problematic. Some early estimates using California attenuation values (i.e., decrease in ground-shaking with distance) gave values as high as 9.5, which would make the 1755 earthquake the world's largest event (Mezcua et al., 1991). Using values of attenuation more typical of Iberia and a conversion formula produced by Abe (1979) gives values of 8.5-8.6 (Teidemann, 1991; 1992).

palaeontological or palynological studies had been published from within the region, with recourse having to be made to sites located outside the Algarve. Secondly, additional radiometric dates were required at several key stages for morphostratigraphical units in the evolutionary chronology. Both these gaps have now been filled and it is possible to propose an account of late Pleistocene and Holocene events that occurred in the Algarve.

<Insert Fig.1 near here>

2. The geological setting

As Figs. 1 and 2 show, the pre-Pleistocene geology defines a number of topographic sub regions in the Algarve. The northern part is dominated by the Monchique massif, which rises to over 900 m and represents an upper Cretaceous syenite intrusion into the Carboniferous country rock. To the south and surrounding the Monchique in the western and eastern Algarve is a formation of folded and faulted Carboniferous metamorphic rocks that produce a rolling upland, from <100 m to >350 m in height. Traditionally this formation has been mapped as schist in Spain and Portugal, but in the Algarve the intensity of regional metamorphism is lower and rocks are more shale-like and have been described as *metasediment* Chester and James (1991). The Algarve littoral zone is generally below 100 m in height and comprises Jurassic to Miocene limestone, silt and marl, deposited in a Mesozoic-Cenozoic basin formed by processes of flexure associated with the collision between Africa and Iberia (Terrinha et al., 1998). Especially, but not exclusively in the area between Lagos and Portimão, lower to middle Miocene limestone, the *Lagos-Portimão Formation*, is overlain by upper Miocene, fossil-poor laminated sandstone (Pais et al., 2000). The Lagos-Portimão Formation is associated with the development of karstic phenomena (Dias and Cabral, 2002); and in coastal sections in the Praia da Rocha area (Fig. 2), solution-enlarged discontinuity planes and cavities are filled with weathered limestone residue and red younger detrital sediments (Roberts and Plater, 1999). Other upper Miocene deposits of more limited outcrop include: the *Mem Moniz* micro-fossiliferous spongolithic limestone; the *Caçela Formation*, a limestone- dominated sequence that is sometimes interbedded with conglomerates and which crops out in the eastern Algarve and near to Lagos; and the *Galvanas Formation* of conglomerates, whose deposition continued into the Pliocene (Telles-Antunes and Pais, 1993; Pais et al. 2000; Carvalho et al., 2009).

<Insert Fig.2 near here>

3. The Pleistocene

3.1. The Ludo Formation

Following articles by Moura and Boski (1994, 1999) the Faro/Quarteira Formation was renamed the Ludo Formation. The Algarve Basin was formed during the opening of the North Atlantic. Its earliest sediments are Triassic and the Ludo Formation represents late filling of the basin during post-Miocene time (i.e., from *ca.* 5.3 Ma). Devereux (1983), who studied sections around Quarteira and Armação (Fig. 1), indicated that the deposits comprise “consolidated sediment with no visible sedimentary structures, consisting almost entirely of red sand with a few rounded pebbles of quartz and iron nodules” (Devereux, 1983, p. 47) and, on the basis of these characteristics, argued in favour of sedimentation in a marine environment. In a later study and following field mapping of outcrops and the examination of sections from the western Algarve to beyond the Spanish border, Chester and James (1995) argued in support of the model first proposed by Raynal (1979) and that the sands represent a *glacis* mountain-foot accumulation, or mantled pediment, derived from erosion in the Algarve interior with aeolian sedimentation being evident in later stages of deposition.

As far as dating is concerned, the situation today is less clear than it was a few years ago. Devereux (1983), Chester and James (1991, 1995) and geological maps published in the late 1980s (e.g., Manuppella et.al., 1987), all suggest a Pleistocene age, because on the Atlantic coast of Portugal just to the north of the Algarve the upper horizons of the Ludo Formation are rich in late Palaeolithic artifacts (Breuil and Zbyszewski, 1946). More recent research has cast doubt on the dating and stratigraphy of these finds, with Raposa et al. (1989) and Clark (2000) arguing for a late Upper Palaeolithic attribution and a date of only *ca.* 8400 years ago. All that can be concluded with certainty is that stratigraphically the Ludo Formation cannot be younger than the late Pleistocene Odiáxere gravels and Loulé sands which overlie it (see section 3.2), or older than the upper Miocene upon which it rests.

The most extensive study of the Ludo Formation to date and one that eliminates most areas of uncertainty, with the exception of its dating, has been undertaken by Boski et al. (1993, 1995), Moura and Boski (1994, 1999) and Pias et al. (2012), who made use of many new sections exposed to the south of a line joining Portimão and Vila Real de Santo Antonio (Fig. 1). Their research has been focused in particular on the Ludo region near Faro, which now gives the formation its name (Fig. 1). Mineralogical, sedimentological and palaeontological analysis shows the formation to comprises four units from the oldest to the youngest: the *Areias de Monte Negro* (Monte Negro sands);

the *Areias de Quarteira* (the Quarteira sands) [2]; the *Areias do Ludo* (the Ludo sands), and the *Areias e Cascalheiras de Gambelas* (the Gambelas sands and gravels), which were deposited under differing palaeoenvironmental conditions (Fig. 3). This classification effectively subsumes the units described by earlier writers. During the Pliocene (ca.5.3-ca.2.6 Ma) it is envisaged that a marine transgression occurred across the Algarve Basin which was constrained by the mountains of the Algarve to the north and deposited the Areias de Monte Negro, the Areias de Quarteira representing continued marine sedimentation under shallow continental shelf conditionsin the Lower Pleistocene. The Areias do Ludo mark the beginning of fluvial deposition during a regressive phase, while later braided streams laid down the Areias e Cascalheiras de Gambelas under semi-arid conditions, with episodes of river incision and deposition continuing into the Middle and Upper Pleistocene (Moura and Boski, 1999; Pias, et al., 2012, pp. 118-120).

A sequence of pre-Pleistocene sands exposed in cliff sections at Olhos de Água and Falésia (Fig. 2), is interpreted as fluvial deposits overlain by beach sands and conglomerates and known as *Areias de Felésia* (Felésia sands) (Cachão, 1995). The Felésia and Monte Negro sands are both overlain by the Quarteira sands and were "probably deposited during the Pleistocene… and therefore the Monte Negro/Felésia sands are in all likelihood formed during the Pliocene" (Pias, et al., 2012, p. 113). This finding is based on $^{87}Sr/^{86}Sr$ dates of 3.0 (+2.5, -1.0) Ma from a fossiliferous layer towards the top of the Felésia sands (Pias, et al., 2000, 2012, Fig. 35, p. 115).

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[2] In the most recently published Portuguese research, the Quarteira sands have rather confusingly once again been referred to as the Faro-Quarteira sands (Pais, et at., 2012, p. 113).

<Insert Fig. 3 near here>

3.2. Odiáxere gravels and *Loulé sands*

Devereux (1983) first mapped and described alluvial fills he found as a discontinuous terrace on the sides of river valleys. He correlated these fills on the basis of sedimentological and geomorphological criteria with similar deposits within southern Europe, northern Africa and the eastern Mediterranean where they were termed the *older (or upper) fill* by Vita-Finzi (1969). Comprising a coarse basal unit, consisting of poorly bedded subangular gravels within a matrix of red silt and clay and an overlying finer sandy unit, today these units are known, respectively, as the Odiáxere gravels and the Loulé sands (Carvalho et al., 2009).

On the basis of local stratigraphy and correlation with similar deposits found elsewhere in southern Europe, sedimentation began in the late Pleistocene, sometime after the deposition of the Areias e Cascalheiras de Gambelas of the Ludo Formation. Traditionally it was suggested that palaeoenvironmental conditions at that time were similar to those posited for the western Mediterranean (see Chester and James, 1999, p. 178): lower sea levels; an anticyclone over the northern European ice-sheet; and a cold, dry climate with episodic intense rainfall (Vita-Finzi, 1969; Devereux, 1983). Dry conditions were ameliorated by the Algarve being more maritime and, hence, more humid than the Mediterranean region to the east. Seasonal precipitation would have been more pronounced, with an intense summer drought and higher winter rainfall. More recent research (Turon et al., 2003; Bicho, 2009) has concluded that:

(i) coastal water temperatures were below 4^{o}C at the Late Glacial Maximum (LGM; i.e., ca.18,000 YBP), with palaeogeographical maps showing rivers extending over part of the continental shelf (Dias et al., 2000);
(ii) before the LGM, pollen diagrams indicate the presence of herbs and shrubs (i.e., *Artemisia* (shrubs) in association with *Chenopodiaceae* and *Ephedra*), low values of *Ericaceae* (shrubs), *Cyperaceae* (sedges) and *Quercus*, *Alnus* and *Betula* (tree) pollen;
(iii) at the LGM, pollen assemblages show the opposite pattern, with *Artemisia* and *Ericaceae* concentrations reversed and tree taxa only being present in small amounts; and
(iv) between 15,000 and 12,000 years conditions returned to those that obtained before the LGM, with colder conditions once again being evident in the pollen data in subsequent Younger Dryas (III) times.

During the time represented by the Odiáxere gravels and Loulé sands the Algarve was settled. A few late Pleistocene/Upper Palaeolithic sites are found in the Algarve (Forrest et al., 2003; Bicho, 2009), but those that do occur are concentrated in the west around Vila do Bispo and show remains of a rich fauna comprising aurochs, goat, horse, rabbit, red deer, tortoise, wild ass, wild boar and a few carnivores (e.g., fox, bear, wolf and lynx). For instance, about 2 km east of Budens (Fig. 1), a site has been excavated in a limestone rock shelter at Vale Boi that dates from 24,300 ± 205 ^{14}C YBP (WK-12 132)[3] and is associated with the exploitation of both land animals and marine fauna (Bicho et al. 2010).

3.3. Pleistocene neotectonics

[3] ^{14}C dates in this paper are uncalibrated because this is the convention normally adopted by most Quaternary scientists and archaeologists working in the Algarve.

In the 1990s and 2000s the Portuguese *Instituto Geológico e Mineiro* (Institute of Geology and Mines) sponsored research on the neotectonics of Portugal. In the Algarve, extensive research on Pleistocene formation has been published by Dias and Cabral (2002) and Cabral et al. (2010), who have documented a large number of deformation structures including joints, faults, and a few folds. It is argued that these structures were produced by two sets of processes:

(i) movement of basement faults; and

(ii) in areas where the Miocene calcareous Lagos-Portimão Formation underlies Pleistocene deposits, local subsidence phenomena caused by the karstification of the underlying bedrock. In addition, near to the coast some soft sediment deformation may be related to liquefaction caused by palaeoearthquakes, which is known to have occurred during the 1755 earthquake (Martínez-Solares and López-Arroyo, 2004).

3.4. Outstanding issues

The marine/subaerial surfaces found to the west of Lagos and the higher fluvial levels described by Feio (1946, 1951) and Devereux (1983), which are discussed in the introduction (section 1), still remain to be linked to the now-established sequence of pre-Pleistocene and Pleistocene events. Additional surfaces have been described by the author, including a possible marine surface at *ca*.70-90 m in the central Algarve near Estoi (Fig. 2) (Chester and James, 1995, p. 147). Morphologically similar levels are found to the north of Lisbon in central Portugal and have been assigned to Marine Isotope stages 3, 4 and 5, i.e., 35,000, 42,000 and 62,000 years ago, by means of AMS radiocarbon and OSL dating. They show a rich suite of Middle Palaeolithic artifacts

(Benedetti et al., 2009). It would be extremely incautious in view of the tectonic instability of the region, to ascribe at least some of the surfaces found in the Algarve to a similar range of ages.

To the southeast of Silves on the limestone belt (Fig. 2), high level rounded quartz gravels occur on isolated summits. The gravels are similar to descriptions of *Ranã* deposits found in central and southern Spain, where they are described as "thin, clast-supported siliciclastic conglomerates of fluvial origin" and are considered to be of Pliocene or early Pleistocene age depending on their height (Gutiérrez-Elorza et al., 2002, p. 356).

With respect to the far west (Fig. 2), low drainage density has enabled undissected surfaces over ca.130 m to be preserved. On these surfaces, pre-Pleistocene sand and gravel is to be found (Chester and James, 1999), with soil profiles showing evidence of continuous soil development since the Pliocene. This area also contains relatively undissected outcrops of pre-Miocene limestone and, in common with the high altitude Monchique, these areas acted as Pleistocene refugia and many endemic floral species are to be found (Mabberley and Placito, 1993).

4. The Holocene

The correlation chart (Fig. 4) summarises the evolution of the geomorphology, vegetation and soils in the Algarve during the Holocene and, although self-explanatory to a degree, a number of features are not fully captured in tabular form and require further discussion.

<Insert Fig. 4 near here>

4.1. The Early Holocene (ca. 10,000 BP - ca.7000 BP)

Within the major south-flowing river valleys of the Algarve, radiocarbon dates from the Loulé Sand unit of the upper Odiáxere gravels and Loulé sands range from 9200 ± 270 YBP (GrN 9918; Janssen and Woldringh, 1981) to 7450 ± 90 YBP (ANU 2815; Devereux, 1983) and show that deposition of this formation continued from the late Pleistocene into the early Holocene. It is tempting, but speculative, to correlate the change from the Odiáxere gravels to the Loulé sand with the Pleistocene/Holocene boundary, with a reduction in river discharge occurring under a warmer climate with less intense rainfall and a rising sea level; but this cannot be confirmed either by the radiometric dates currently available, or by a detailed reading of the palaeoenvironmental evidence (Fig. 4).

At the LGM (i.e., ca.18, 000 BP) and based on evidence from cores and estuarine deposits, the coastline of the Algarve was situated up to 40 km to the south of its present location, with sea level ca.140 m lower. At the beginning of the Holocene comparative figures were up to 20 km and ca.40 m, respectively (Boski et al., 2002; Lario et al., 2002), and thereafter rates of sea-level rise were rapid (i.e., 5-8.5 mm yr $^{-1}$), with the salt marsh loving foraminifera, *Trochammina*, being deposited in the clay-rich sediments of the Guadiana estuary (Boski et al., 2002, 2008).

On the basis of pollen and other palaeoenvironmental indicators (Fig. 4), climatic change in the early Holocene may be summarised as an overall warming trend leading to stability within catchments and a progressive increase in forest cover. Although the earliest stages of the Holocene were probably characterised by a mixed forest/scrub/open ground vegetation mosaic under a warm dry continental climate, from ca 9000 BP evidence implies warmer and wetter conditions with an expansion of *Quercus* (oak) forest and evergreen taxa (e.g., *Olea* (i.e. olive), *Phillyrea* and *Pistacia*) (Fletcher et al., 2007). Extensive soil development occurred, reflecting increased biomass, greater water availability and continuing high temperatures (James and Chester, 1995; Chester and James, 1999).

Recent archaeological publications have argued for a continuity of Upper Palaeolithic culture from the late Pleistocene to the early Holocene (Clark, 2000). This creates a problem because cultures dating from the early Holocene should strictly be termed Mesolithic, and to overcome this methodological difficulty, Bicho (1994) has suggested the term Epipalaeolithic to denote sites of Holocene age with upper Palaeolithic characteristics (ca.10 - 8500 BP, with Mesolithic being reserved for later settlements within the early Holocene. As mentioned in section 3.2, the late Pleistocene upper Palaeolithic was characterized by a rich fauna of aurochs, goat, horse, rabbit, red deer, tortoise, wild ass, wild boar and a few carnivores (e.g., fox, bear, wolf and lynx); but early Holocene environmental change caused the elimination of wild ass, tortoise and bear. In Epipalaeolithic and Mesolithic times, settlements were located close to the coast and concentrated in the western Algarve, with the former culture being associated with hunter-gatherer lifestyles; whereas Mesolithic people formed more settled communities and exploited the coastal and estuarine resources. Common mollusca included *Monodonta lineata* (turban), *Patella* (limpet), *Mytilus* (mussel), *Pollicipes* (barnacle) and *Thais haemastoma* (dog winkle/drill) (Bicho, 2009). Human population numbers are unquantified, but are inferred to have been low; and in neither the Epipalaeolithic nor the Mesolithic was the impact on the environment significant (Allen, 2003; Bicho, 2004; Bicho and Haws, 2008).

4.2. The Middle-Late Holocene (ca.7000 BP to AD 1900)

In comparison with the period after 3000 BP, relatively little is known about the earliest part of the late Holocene. For southern Iberia as a whole, Castro (1995, p. 369) argued that "in late prehistory the driving force of technical and economic progress was essentially linked to metal resources and early metallurgists located in those regions in which copper and silver were either available or accessible." This means that the major anthropogenic impacts on the environment were felt in southeast Spain and to a lesser extent in the Huelva Province immediately to the east of the Algarve. The impact of human activity on southern Portugal was minimal and, according to the archaeological evidence, was confined to limited deforestation by the first Neolithic farmers and herders who inhabited the region from ca. 6000 BP (Bicho, 2009). Neolithic sites are located at and near the coast (Carvalho, 2010), and the exploitation of marine resources was certainly important in the early stages of occupation and probably for much longer (Stiner et al., 2003).

Human-induced deforestation probably became more intense by *ca.*4000 BP (Fletcher et al., 2007; Mendes et al., 2010). Samples of bones and seeds from archaeological sites in southwest Spain (Chapman, 1985; Stevenson and Harrison, 1992) are suggestive of mixed farming at *ca.* 6400 BP based on barley, wheat, pigs, goats and cattle, with the more limited number of sites in the Algarve reflecting the region's more impoverished resource base and/or the less intensive archaeological research that has been carried out. Sites from the Copper Age are found at Alcalar in the central Algarve and Santa Justa near to Alcoutim (Fig. 1), but by the early Bronze Age a denser settlement is evident from site distribution maps (Castro, 1995, p. 88), which show a coastal concentration especially in the lower Guadiana valley and Portimão/Lagos areas (Fig. 1).

Under low population pressure, the conditions of environmental stability noted in the early Holocene were enhanced, with pollen diagrams showing colonization by *Quercus suber* (cork oak) and other tree species, and well-developed soils being found over most geological substrates (Fig. 4). Geomorphological mapping in the inland valleys (Chester and James, 1991, 1999) shows considerable valley development, with the Odiáxere gravel/Loulé sand being incised by up to 50 m under conditions of reduced sediment supply from heavily vegetated catchments and a sea level that was still lower than that found today. Reduction in sediment supply meant that by about 3000 BP the mouths of rivers draining into the Baía de Lagos (Pereira et al. 1994) were largely sediment free. Slightly later the Boca do Rio (Fig. 2) was an open estuary (Allen, 2003).

Between the beginning of the first millennium B.C. and the early Middle Ages (i.e., 3000 BP – ca. 700 BP) the impact of people on the landscape of the Algarve was greater than at any time in the Holocene, with the possible exception of the past 100 years. In southern Iberia horses, were introduced on a large scale from ca.3000 BP. After 2700 BP additional animal species were found for the first time (e.g., sheep, donkeys and chickens); and new crops were cultivated including vines, olives and pomegranates (Stevenson and Harrison, 1992).

From the time of the Iron Age and Roman settlement of the region, however, anthropogenic influences increased in significance, becoming the dominant factors controlling landscape change during the period of Islamic settlement that occurred between the eighth and the end of the thirteenth centuries A.D. (Marin, 1998; Teichner and Neville, 2000). In Spain this civilisation is known as *al-Andalus* and at its height was centred on Córdoba (Boone, 2009); whereas in the southern Portugal the Islamic period was shorter and only lasted from the eight century to A.D. 1249 when Faro fell to Christian forces, but its impact on the landscape was no less significant. According to a detailed reconstruction by Boone and Worman (2007) of the lower Alentejo region just to the north of the Algarve, sometime after the dissolution of Roman control in the fifth century A.D. there was an increase in population as evidenced by settlement density and growth. Small hamlets and villages appeared and over the next 500 years their density increased sixfold with the most intensive impact on the landscape coinciding with the *Umayyad Caliphate*, which ruled the region in the mid-tenth century A.D. [4]

In the Algarve the major impact of Roman and Islamic phases of settlement was felt in the interior valleys, particularly those in which land clearance occurred on the easily eroded hills of the interior formed by schists (Fig. 4). At Silves (Fig. 1), which was the centre of Muslim influence, the historical record is particularly rich; and according to the contemporary writer Idrisi (or Edrisi ca. A.D. 1099-1165 – see Kimble, 1968, pp. 56-60), the city's prosperity was based on a rich irrigated agricultural hinterland and a river-based trade geared to the export of citrus fruits and forest products (Stanislawski, 1963, pp. 184-85). The Carboniferous schist is fissile, often dips downslope at high angles, and calculated erosion rates from sample plots at Mértola to the north of the Algarve show that erosion is over 1000 times greater on bare soils on schist than on plots covered by

[4] Boone and Worman (2007, p. 119, 123) based their reconstruction on 26 radiocarbon dates obtained on material recovered from archaeological sites ranging in age from 1385 ±55 YBP (AD 647) to 198 ± 46 YBP (AD 1771). Unusually for southern Portugal, these are expressed as both un-calibrated and calibrated dates.

garrigue vegetation (de Brito, 1994, p. 63). As Fig. 4 shows, this phase of the Holocene was not only associated with palynological evidence of human-induced environmental change but also with widespread sediment transport and deposition within inland valleys. Up to 3 m of sediment was deposited in valley floors as a *Holocene terrace*, comprising topsoil and inorganic fine materials, with mineral magnetic properties and the occurrence of charcoal pointing strongly to fire being used to clear the land. The Holocene terrace (Fig. 4) may be dated and near to Silves (Fig. 1) the author and his colleague excavated sediment which yielded a radiocarbon date of 2690 ± 70 YBP (Ox A 2287) at its base together with Roman pottery and Islamic glass in the mid-section (Chester and James, 1991). At the coast the effect of enhanced sediment supply was widespread silting of river mouths and estuaries. The mouths of rivers draining into the Baía de Lagos were choked with sediment (Pereira et al. 1994); at Boca do Rio siltation was noted in the post-Roman period, while in the Guadiana valley human activity leading to deposition may be inferred from the sedimentary record (Mendes et al., 2010).

In the southern Alentejo, just to the north of the Algarve and on the basis of their detailed survey of radiocarbon dated archaeological sites, Boone and Worman (2007) argued that 50-100 years before the Christian reconquest many rural settlements were abandoned because of land degradation as new settlers chose to locate on thicker soils found in valleys rather than on the hilltops and valley slopes that were preferred in Islamic times. There is a *gap* in dated sites between the middle of the twelfth to the middle of the fourteenth centuries. In the Algarve settlers, whilst maintaining irrigation and the cultivation of citrus fruits, developed an agricultural system of intercropping of cereals, tree crops and vegetables that was little different from that found over much of central and northern Portugal (Stanislawski, 1963, p. 10, 14). The focus of agricultural activity shifting southwards to the limestone belt (Fig. 2), with the coastal lowlands retaining the importance they had held since before Roman times. This *new* agricultural system served to reduce erosion, largely because the easily eroded soils on the schistose hills to the north of Silves (Fig. 2) were less intensively exploited (Chester and James, 1999). As Fig. 4 shows, *garrigue and maquis* vegetation covered the schistose hills that were used mainly for low intensity grazing. Sediment supply was reduced, with the effect that until the early years of the twentieth century A.D. the Holocene terrace deposits were incised. At the coast, channels were cut through the sediments that had accumulated within the estuaries of rivers draining into the Baía de Lagos and other coastal lowlands during the Roman and Islamic periods.

When first writing about Holocene terrace deposits, Devereux (1983) followed the lead of Vita-Finzi (1969) by explaining the synchronicity of deposition throughout southern Europe and the circum-Mediterranean by means of subcontinental climatic control. Although the balance of argument now favours anthropogenic factors as being predominant in the Algarve and elsewhere (see Chester and James, 1999, pp. 184-185 for detailed arguments and references), this is not to claim that some environmental forcing was not of significance in the late Holocene. For example, between 4450 and 3850 years ago, during the transition from the late Copper to the Bronze age in southern Iberia, many settlements were abandoned or re-established. Lillios (1997, p. 187) made the point that synchronicity across such a large region may point to climate control, but admitted that social and cultural change may be equally important.

4.3. Holocene tectonic activity

For the early Holocene, Bicho and Haws (2008, p. 2171) argued that dissimilarities in the distribution of archaeological sites between the eastern and western Algarve may have been caused by differential tectonic movement. In the eastern Algarve not only is there evidence of marine submergence with late Pleistocene and early Holocene surfaces being covered by later sediment, but the archaeological record is also sparse with an absence of sites older than the Mesolithic. Buried estuarine deposits and beaches indicate compaction of marshy deposits and tectonic subsidence of the coastal area between Tavira and the Guadiana estuary (Fig. 2). In contrast, in the western Algarve archaeological sites represent a much wider age range and there is evidence of Holocene uplift of the coastal shelf.

Inferred differential fault movements in the early and middle Holocene are but one instance of active tectonics leaving an imprint on the landscape. Lists compiled by Costa et al. (2005) and Chester and Chester (2010) show that at least 14 earthquakes with a magnitude of 7 or greater have affected the region since the estimated magnitude 8.5 Cabo de S. Vincente event of 63 B.C. (Fig. 2), but details of the impacts of most of these events have either not been researched or have left records that are too fragmentary to allow detailed study. In addition, the small number of large earthquakes recorded in earlier times is suggestive of an incomplete record. Notwithstanding questions of data quality, over time-scales of 10^3–10^4 years events of a magnitude of 8.5 may occur as frequently as 614 ± 105 years (Mendes-Victor et al. 1994, p. 269), though return periods of ca.1000 and 1479 years have been estimated by more recent writers (Chester and Chester, 2010, p. 364). Some idea of how important such events may have been as agents of landscape change throughout the Holocene can be gauged from the 1755 Lisbon earthquake, the effects of which have been researched in detail by the author using archival data and are summarised in Table 1.

<Insert Table 1 near here>

4.4. Recent pressures on the landscape

Figure 4 does not continue beyond A.D. 1900, but human impact on the landscape did not cease and in the last 100 years has probably been as intense as at any time since the period of Roman and Islamic settlement. The effects have been felt within inland valleys and at the coast.

With respect to the former, using historical cartography and aerial photographic evidence, Devereux (1983) observed that interior river valleys were decreasing in depth, because of deposition of material eroded from catchments, and that higher discharge rates caused significant lateral erosion. As in the period between ca. 3000 BP and ca. 700 BP, the key to understanding the reasons for this situation lie in the land use being carried out on the areas underlain by schist (Fig. 2). One hundred years ago catchments were largely stabilized under a cover of *garrigue* and *maquis* vegetation; but, at the beginning in the First World War (1914 - 18) and becoming more intense under the authoritarian government of the *Estado Novo* (New State), which ruled Portugal from 1928-1974, the country strove to be self-sufficient in food. This involved a wheat campaign (*campanha do trigo*) that saw vast swaths of land on the schistose hills being cleared of *garrigue* and planted to grains (Stanislawski, 1963, pp. 189-203; Chester and James, 1999, p. 188). Sediment yields were up to 250 times greater on cropped land than on *garrigue* (de Brito, 1994, p. 63); and when the Arade dam above Silves (Fig. 1.) was investigated in 1973, it was found to have lost 10% of its storage capacity in just 17 years since it had been constructed (Brouwer and Ryckborst, 1975). A landscape dominated by cereal cultivation was still widespread in the 1950s (Carta Agricola e Florestal de Portugal, 1957) and declined thereafter, but in the 1980s and 1990s high sediment yields were maintained as the schistose hills in the western Algarve were planted with extensive stands of *Eucalyptus globulus*, a tree species introduced from Australia. Field research by the author showed that techniques of stripping *garrique* and preparing the land using heavy machinery led to widespread soil disturbance, gullying and sheetwash, with much sediment being observed within small reservoirs constructed for firefighting after only a few days of heavy and persistent rain (Chester and James, 199, p. 188). Changes in rainfall regime may have also been important in part in enhancing erosion in the twentieth century (Loureiro and Coutinho, 1995), but the observed erosion from cleared slopes and the rapid siltation of reservoirs, and particularly those found within cleared catchments, strongly points to the overwhelming influence of anthropogenic factors.

At the coast change has also been profound as a result of the impact of tourism on geomorphological processes. Since 1900 a tide gauge at Lagos has shown a secular rise in sea level of *ca.*1.5 mm yr $^{-1}$ (Dias and Taborda, 1988; Ferreira et al., 2008), but rapid coastal retreat during the past half-century in cliffs formed of easily eroded rocks, of which those formed in materials of the Ludo Formation are the most noteworthy, has been enhanced by mechanisms related to human pressure. In contrast, other features related to tourism, particularly beach replenishment, have increased coastal stability and both elements of human impact are summarised in Table 2.

<Insert Table 2 near here>

5. Conclusions

Since 1980, considerable progress has been made in improving our understanding of Pleistocene and Holocene geomorphological development in the Algarve. A model explaining the deposition of the Pleistocene Ludo Formation and Odiáxere gravels/Loulé sands has been proposed by Moura and Boski (1994, 1999). The model allows the inclusion of earlier ideas about the varied geomorphological processes (i.e., marine transgressions/regressions and fluvial activity) that were responsible for its development, which are now shown to have occurred at different times during a long - period of sedimentation from the Pliocene to the middle or even the early upper Pleistocene.

Within the late Pleistocene/early Holocene evidence from sedimentary archives now allows the conditions under which the fluvial Odiáxere gravels/Loulé sands were deposits to be defined. Some earlier events and palaeoenvironments still remain to be fully researched and incorporated into the established stratigraphical system. These include putative marine/subaerial levels in the extreme west, and gravel spreads, which are preserved on limestone summits in the central and eastern Algarve.

In the Holocene and up to ca. 3000 years ago, the Algarve landscape developed under the control of physical factors alone. Conditions became progressively warmer and wetter until ca. 5000 years ago and drier later, with the vegetation stabilizing slopes, allowing soils to develop and so reducing sediment movement. During the past 3000 years, the landscape has been shaped by a mixture of human and physical factors — the most profound changes coinciding with two distinct time periods: the episode of Roman and Islamic rule (ca. 3000 BP – ca. 700 BP); and the 100 hundred years, especially after tourist pressure became acute from A.D. 1960.

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Fig. 1. The Algarve: relief and location map (modified and updated from Chester and James, 1995, Fig. 1, p. 135).

Fig. 2. Geological maps: (A) *Barlavento* (Western) Algarve and (B) *Sotavento* (eastern) Algarve (modified and updated from Chester and James, 1995, Fig.1, p.136).

Fig. 3. Vertical profile through the Ludo Formation, showing the stratigraphy of its four units (modified and simplified from Moura and Boski, 1999, Fig. 2, p. 89). According to Pais et al. (2012, pp. 113-116), the Monte Negro sands are contemporaneous with the Falésia sands (see 3.1) and were deposited in the late Pliocene i.e., before 2.6 Ma. The date of 35-40,000 BP for upper limit of the formation was first suggested by Chester and Duncan (1995) and is accepted by Pais, et al. (2012).

Fig. 4. Algarve: Holocene correlation chart: *ca*. 10,000 BP to A.D 1900. The vertical axis is not to scale. (a) Stratigraphical timescale (based on: Cremer et al. 1992; Gibbard and Cohen, 2008). (b)Principal geomorphological events at the coast (based on: Dias and Taborda, 1988; Dias and Neal, 1992; Dias et al. 2000; Pereira et al. 1994; Zazo et al., 1994, 1996; Boski et al. 2002; Allen, 2003; Ferreira et al. 2008; Matias et al. 2009 and the references cited in the table). (c) Principal geomorphological events in the inland valleys. In earlier papers the author termed the *Holocene valley fill*, the *lower* (or *younger fill*) (Chester and James 1991, 1999) following the usage of Vita Finzi (1969). The term *Holocene terrace* is preferred because is the term used in recent Portuguese research, though it has not been formally described as a formal stratigraphical formation (Carvalho et al. 2009). (d) Pollen record from Portugal (based on information from: the Serra da Estrela Central Portugal - Janssen and Woldringh, 1981; the Algarve - Fletcher et al. 2007 and Southern Spain - Pons and Reille, 1988 and Stevenson and Harrison, 1992). (e) Soil development (based on: Chester and James, 1995, 1999; James and Chester, 1995, references cited in the table and unpublished field data).

Table 1. Effects of the 1755 'Lisbon' earthquake on the landscape of the Algarve (for locations see Figs.1 and 2; based on information in Chester and Chester (2010), the references cited therein and unpublished field data).

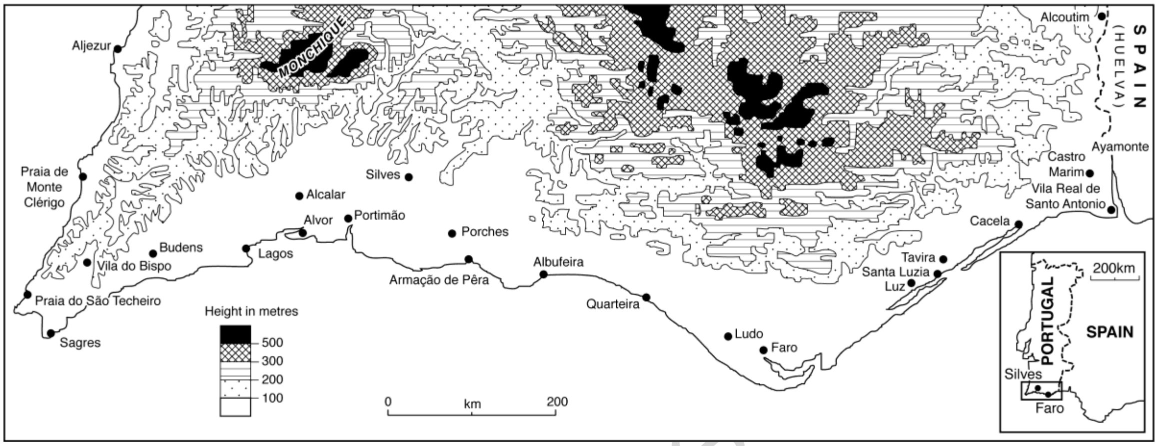
Location	Summary of effects
Praia do Telheiro (west coast)	A major 0.85 - km - long landslide was triggered by the earthquake.
Cabo do S Vicente to Lagos	An estimated 30 - m tsunami affected Sagres, and angular blocks up to 4500 kg were deposited. To the east of Sagres at Martinhal a 2 - km marine incursion occurred. At the Boca do Rio, a sediment core reveals that sediment representing ca. 700-800 years of deposition was eroded by the tsunami. Here and elsewhere the tsunami was associated with (a) both erosion and deposition; (b) most of the material deposited was not from the offshore zone but from beaches and dunes (often containing shell fragments) (c) the rapid deposition of chaotic assemblages of differing grain size; and (d) documented run - up heights were higher than the upper altitudinal limit of sedimentation. At Lagos, the sea penetrated inland by 2.5 km.
Lagos to Portimão	At Alvor, the harbour was choked with sediment; and after the tsunami only small craft could be handled. At Portimão, inundation reached 880 m inland and spread 5 km up the Rio Arade. Waves at the coast may have been *ca.* 20 m at Alvor.
Portimão to Albufeira	In Albufeira and Quarteira, there were many changes in ground level from aggradation and erosion, producing areas of impeded drainage, with stagnant pools subsequently becoming malarial.
Albufeira to Faro	The Ria Formosa barrier system saved the city from severe tsunami damage, but major changes occurred in the offshore islands. Several rivers were choked with sediment.
Faro to Castro Marim	Near to the mouth of the Rio Guadiana, increased erosion occurred and the settlement of Santo António de Arenilha was washed away. The tsunami drowned the easternmost portion of the Ria Formosa barrier islands, which before the earthquake had extended to the Guadiana estuary. Sand moved inland and covered the former lagoon formed behind the barrier.
General effects	Many small changes in the relative altitude of the land and sea are noted in the literature and many small rivers were choked with sediment near their mouths. Small coastal

landslides frequently occurred.

Table 2. Factors affecting contemporary coastal processes in the Algarve (based on Chester and James, 1999, fig. 5, p. 190 and updated by the references cited).

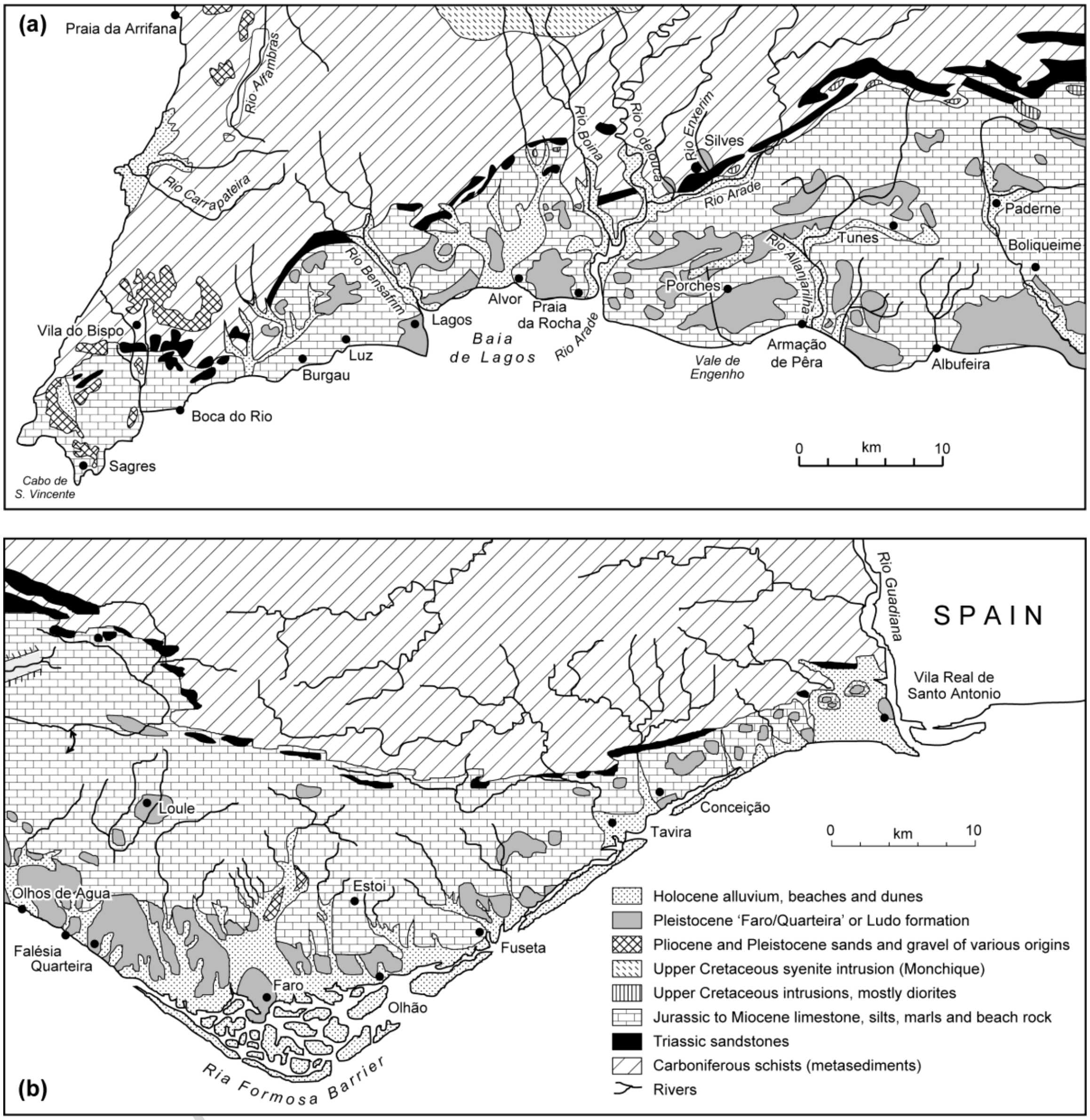
Tourist-related activities enhancing erosion	**Effects on Coast**
Cliffs formed in the Ludo and other formations that lack erosion resistance (after Dias and Neal, 1992; Pereira, 1996a)	
(a) Irrigation of gardens and golf courses increases top loading of cliffs increases pore water pressure in the slope materials. Increased runoff on impermeable surfaces (e.g., streets, car parks) results in more frequent flows in gullies, and these processes in combination lead to enhanced erosion. On beaches, small alluvial fans are often at the mouth of gullies.	Between 1983 and 1998 mean rates of retreat were as high as 3.2 m yr^{-1}, with these figures being much higher in some years (Dias and Neal, 1992). These very high rates of retreat — but not the reality of the process — are disputed by Marques and Andrade (1993). High rates of retreat may have started before the era of mass tourism, being caused by rising sea levels and major storms in the 1920s and 1930s.
(b) Traffic increases the top-weight and induces dynamic loading, so enhancing cliff failure.	
(c) Construction of buildings on the top of cliffs increases vertical loading and instabililty.	
(d) *Graffiti* and caves cut by tourists into cliffs produce undermining.	
(e) In the 1980s and 1990s the legal prohibition on building within 50 m of cliff tops was often ignored, enhancing problems of excess top weight.	
(f) To the east of Quarteira (Fig. 2) and elsewhere, beach width is reduced because of the construction of a marina and jetties.	
(g) The construction of groins and other sea defenses to prevent beach loss in one area, reduces beach width in other areas where cliffs are susceptible to erosion (e.g., the Ludo Formation at Quarteira).	
Other formations (after Pereira, 1996a b)	
In the Baía da Lagos, disruption of systems of sediment transport between the two sides of the bay occurred, because of jetty construction. Tourist pressures have partly destroyed dunes and enhanced erosion.	From 1990-1996 beach width was reduced by *ca.* 30 m.
Tourist- related activities to enhance stability	

Beach replenishment.	In the Vale do Lobo (near Quarteira) and at Praia da Rocha this has been successful and has reduced cliff erosion (Cruz de Oliveira et al., 2008) The Cacela peninsula (Fig.1) was highly susceptible to erosion by overwash events before beach nourishment was undertaken (Matias et al., 2005).



Aljezur
MONCHIQUE
Alcoutim
SPAIN
(HUELVA)
Praia de Monte Clérigo
Silves
Alcalar
Alvor
Portimão
Porches
Budens
Lagos
Vila do Bispo
Praia do São Techeiro
Sagres
Armação de Pêra
Albufeira
Quarteira
Ludo
Faro
Tavira
Santa Luzia
Luz
Cacela
Castro Marim
Ayamonte
Vila Real de Santo Antonio
Height in metres
500
300
200
100
0
km
200
200km
PORTUGAL
SPAIN
Silves
Faro

Fig. 1



(a)
Praia da Arrifana
Rio Alfambras
Rio Carrapateira
Rio Boina
Rio Odelouca
Rio Enxerim
Silves
Rio Arade
Paderne
Tunes
Boliqueime
Rio Alcantarilha
Porches
Rio Bensafrim
Lagos
Alvor
Praia da Rocha
Vila do Bispo
Luz
Burgau
Baia de Lagos
Rio Arade
Vale de Engenho
Armação de Pêra
Albufeira
Boca do Rio
Sagres
Cabo de S. Vincente
0 km 10
Rio Guadiana
SPAIN
Vila Real de Santo Antonio
Loule
Conceição
Tavira
0 km 10
Olhos de Agua
Estoi
Falésia Quarteira
Faro
Fuseta
Olhão
Ria Formosa Barrier
(b)
Holocene alluvium, beaches and dunes
Pleistocene 'Faro/Quarteira' or Ludo formation
Pliocene and Pleistocene sands and gravel of various origins
Upper Cretaceous syenite intrusion (Monchique)
Upper Cretaceous intrusions, mostly diorites
Jurassic to Miocene limestone, silts, marls and beach rock
Triassic sandstones
Carboniferous schists (metasediments)
Rivers

Fig. 2

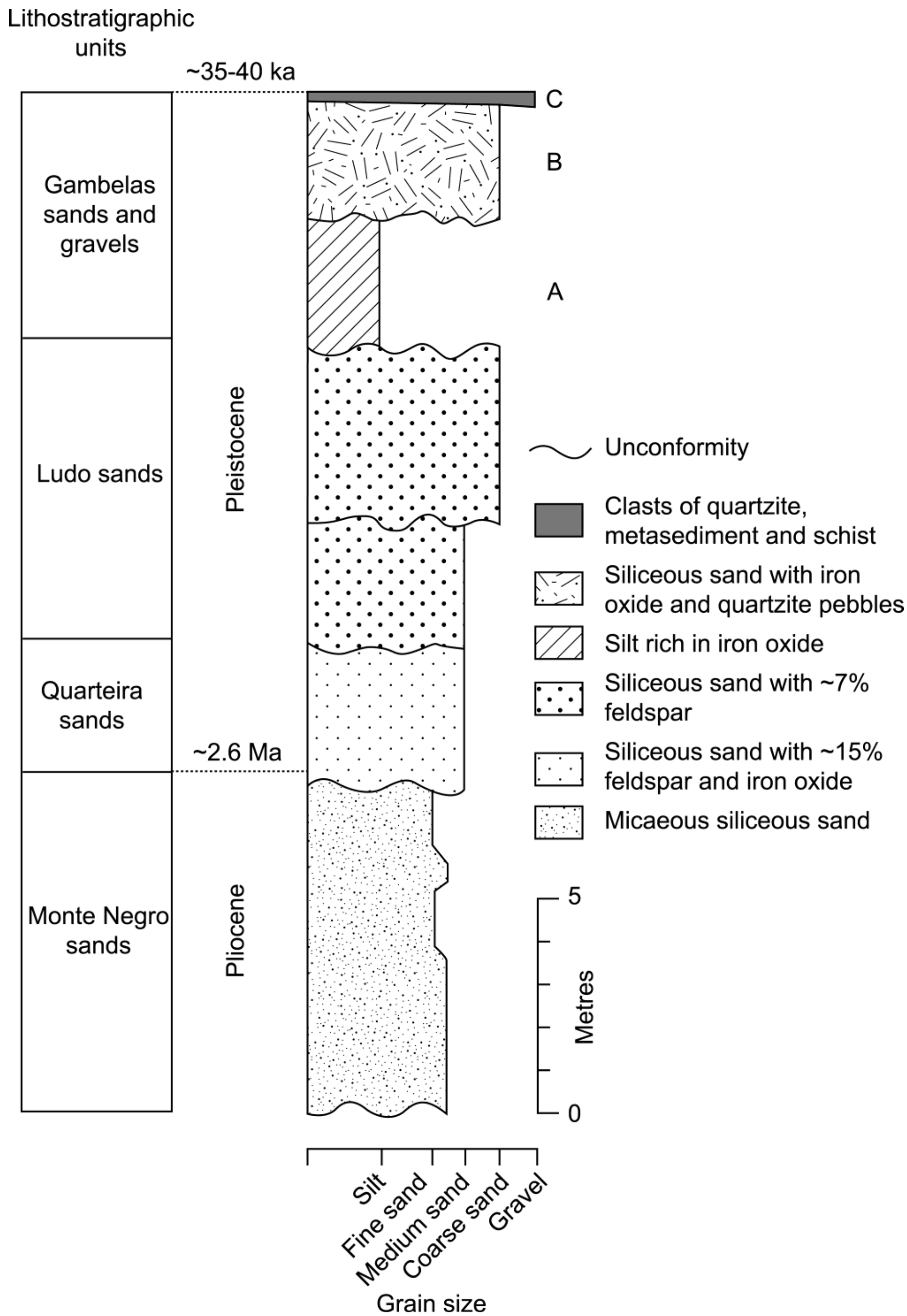

Lithostratigraphic units
~35-40 ka
Gambelas sands and gravels
Ludo sands
Quarteira sands
~2.6 Ma
Monte Negro sands
Pleistocene
Pliocene
C
B
A
Unconformity
Clasts of quartzite, metasediment and schist
Siliceous sand with iron oxide and quartzite pebbles
Silt rich in iron oxide
Siliceous sand with ~7% feldspar
Siliceous sand with ~15% feldspar and iron oxide
Micaeous siliceous sand
5
0
Metres
Silt
Fine sand
Medium sand
Coarse sand
Gravel
Grain size

Fig. 3

STRATIGRAPHIC TIMESCALE [(a)]		PRINCIPAL GEOMORPHOLOGICAL EVENTS AT THE COAST [(b)]	PRINCIPAL GEOMORPHOLOGICAL EVENTS IN INLAND VALLEYS [(c)]	POLLEN RECORDS FROM PORTUGAL AND SPAIN [(d)]	SOIL DEVELOPMENT [(e)]
ISOTOPE STAGE	LATE HOLOCENE	Studies at Baía de Lagos show a slow trangressive trend from *ca* 0.25 ka (Pereira *et al.,* 1994). The tsunami of 1755 drowned much low-lying coast including the Boca do Ria and the Ria Formosa Barrier (Fig. 2) and caused other effects on the landscape (see text). Further siltation, punctuated by erosion during major storm events, occurred between 1755 and A.D.1900.	Incision of the Holocene terrace (lower fill), by up to 3 m.	Pollen assemblages show features indicative of the influence of people e.g., large increases in chestnut, olive, juniper, and various types of cereal, suggestive grazing and the cultivation of cereal crops.	**Lowlands:** Stability under traditional farming. Uplands (Serra): Shifting cultivation around farmsteads and hamlets. Extensive grazing of *garrigue/maquis*. Brown soils are developed on the syenite soils on the Monchique massif. Terraces date from the early nineteenth century onward (Stanislawski, 1963, p. 43) to support arable farming. Un terraced slopes carry chestnut, cork oak and pine.
		~ 0.7 ka	~ 0.7 ka		
		Rates of sea level rise averaged 1.5 to 2 mm Yr^{-1} (Lario *et al.,* 2002) Siltation of estuaries reached its maximum extent at 0.5-0.25 ka, much of the sediment being fluvial and derived from inland (Schneider *et al.,* 2010). A minor regressive event at *ca* 0.5 ka was probably associated with the northern hemisphere neoglacial.	Deposition of Holocene terrace deposits (lower fill). Depth in excess of 3 m. Radiocarbon date near to the base 2690 ± 70 BP – OX A 2267 (Chester and James, 1991).	Expansion of shrubland, with rock rose and heather pollen increasing under the influence of a drier climate and increasing anthropogenic activity (Fletcher *et al.,* 2007). In southern Spain diagrams show widespread clearing and burning until *ca* 0.75 ka.	**Lowland:** Lower fill and structural basins in limestones develop brown soils that support intensive cropping. Topsoil of terra rossa in the limestone belt (Fig. 2) is eroded following removal of oak dominated woodland. Traditional Mediterranean farming (olives, vines, figs, grain, carob, vegetables and grazing) becomes established throughout most of the lowland. Pastoral farming on the plateau gley soils of the extreme west. **Uplands (Serra):** Major erosion of hillslope soils is evident from *ca* 3 ka. Colour, mineral magnetic properties and organic and charcoal content of resulting fill point to widespread, brown topsoil erosion sourced from burned catchment slopes. Brown alluvial soils develop on stable terraces (upper fill) within major valleys in the Serra. Soil development resumes under regenerated garrique cover on red, iron-rich, truncated hillslope soils and support shifting cultivation around farms. Un terraced slopes carry chestnut, cork oak and pine.
		~ 3 ka	~ 3 ka		
		Studies at Boca do Rio (Allen, 2003) and Armação de Pera (Moura *et al.,* 2007) indicate that by *ca* 5 ka sea levels were broadly similar to those of today, although Dias *et al.,* (2000) place the time somewhat later at *ca* 3.5 ka.	Incision of the Odiáxere gravels/Loule sand.	In Huelva, diagrams show colonization by cork oak from *ca* 6 ka to *ca* 3.6 ka Expansion of oak forest and thermo 'Mediterranean' e.g. evergreen taxa (eg *olive, Phillyrea* and *Pistacia*) reflecting a warm, moist, oceanic climate between the base of the Holocene and *ca* 5 ka.	Under progressive climatic amelioration and forest extension, brown topsoils develop in all sediments and in truncated Pleistocene or older *terra rossa* soils. Podzolization occurs in highly weathered rocks in the extreme west. Gleyed soils occur on plateau surfaces near Vila do Bispo (Fig. 1). Un terraced slopes carry chestnut, cork oak and pine. Pedogenesis occurs as erosion rates decrease and deposition rates of the upper fill decline to *ca* 7.5 ka. Red soils continue to develop on Late Pleistocene sediments of the lowlands and in the upper fill terraces in upland valleys.
		~ 7 ka	~ 7 ka		
	EARLY HOLOCENE	Early Holocene transgression. At *ca* 10 ka the coastline was well to the south of its present position (Dias et al 2000; Hilbich *et al.,* 2008). Between *ca* 10 ka and *ca.* 7 ka estimates of sea level rise vary from 5 mm yr^{-1} (Lario *et al.* 2002) to 8.5 mm yr^{-1} (Boski *et al.,* 2002). Dunes formed from *ca* 9 to 7 ka.	Deposition of the Odiáxere gravel and the Loule sand. It is possible that the former is late Pleistocene in age, whereas the latter dates from the early Holocene (see text). Best preserved as 'relict' features on valley spurs at height up to 50 m.		

Fig. 4

Highlights

* Origin and extent of Pliocene/ Pleistocene *Ludo Formation.*

*Deposition of upper-Pleistocene/early-Holocene fluvial *Odiaxere gravel & Loule sand.*

*Anthropogenic role in upper Holocene terrace sedimentation.

*Contemporary human pressures on the landscape.