Version of 27/2/08

The effects of the 1755 Lisbon earthquake and tsunami on the Algarve Region, Southern Portugal

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Key words: Portugal, 1755 earthquake, tsunami, hazard analysis

ABSTRACT

The 1755 Lisbon earthquake (magnitude ~8-5M*w*) killed between 15 and 20,000 people, of whom an estimated 1,020 lived in the Algarve. The earthquake cost Portugal between *c*.32 and 48% of its *Gross Domestic Product*, probably making it financially the greatest natural catastrophe to have affected western Europe. Using a combination of archival information and data collected in the field, this paper discusses: the devastating effects of the earthquake and tsunami on the economy, society and major settlements in the Algarve; and recovery of the region in the years that followed. Today the Algarve is one of Europe's principal tourist destinations and a region vital to the Portuguese economy. The 1755 earthquake was not a one off event and the Algarve, which now houses a resident population of over 400,000 – a figure that more than doubles with tourists in the summer months, is highly exposed to earthquakes and tsunamis. An earthquake of similar size (minimum estimated recurrence 614±105 years), is viewed as a *worse-case future scenario*. Although strict building codes which apply to the whole country were pioneered in Portugal following 1755 and have been revised on many occasions, there is a recognised need for more detailed hazard maps and emergency plans for the Algarve. These have already been produced for Lisbon and in the Algarve a start has been made, where a tsunami risk map has recently been completed for Portimão *concelho* (i.e. county).

A. INTRODUCTION

On Sunday 26 December 2004 the countries bordering the Indian Ocean were devastated by the fourth largest earthquake to have affected the world since 1900, and the highest magnitude event since Prince William Sound in Alaska was struck in 1964. With an epicentre located 225 km south southeast of Banda Aceh in Sumatra (Indonesia) and a moment magnitude (M*w* – see glossary) of *c.*9.0, official tallies estimate the number of deaths at over 180,000, some months later more than 230,000 people in some twelve countries were still unaccounted for and more than 1.7 million people had lost their homes (Shepard, 2005; USGS, 2005).

It is easy to forget that Western Europe has also suffered the effects of major earthquakes and that the greatest disaster to have befallen the region occurred just over 250 years ago when the *Lisbon earthquake*, not only destroyed about a third of the buildings in Portugal's capital city, but also devastating much of southern Iberia and north Africa (Fig. 1); with the effects of its tsunamis being felt with decreasing force as far away as the Caribbean and the British Isles (Degg and Doornkamp, 1994). Comprising three main shocks and many aftershocks, the duration of ground shaking in Lisbon was *c.*10 minutes and, although estimates vary, it is likely that the earthquake's magnitude was at least 8.5 (M*w*); affecting an area of *c.*800 000 km^2, through a combination of earthquakes and tsunamis (Kozák and Thompson, 1991; Tiedemann, 1991: 23). In recent years estimates of death have been reduced as a more reliable historical data have been analysed. In the past many text books quoted figures of 40-70,000 (e.g. Bolt, 1999), but the total number of deaths in Portugal probably did not exceed 12, 000 from all causes (i.e. earthquake, tsunami and fire), of whom *c.*10, 000 lived in Lisbon. Many victims resided in Spain and Morocco, but in the latter case there is some confusion in both Arabic and European sources between the event of 2 November and the effects of local earthquakes which occurred on 18 and 27 November (Levret, 1991). For Portugal, Spain and Morocco as a whole a figure of 15-20,000 deaths has been proposed (Martínez-Solares and López-Arroyo, 2004), of whom an estimated 1,020 resided in the Algarve (Costa *et al.*, 2005). Estimates vary, but taking the population of Lisbon as 150,000 (Marques, 1976) then a mortality statistic of *c.*10, 000 for Lisbon represents *c.*7% of the city's inhabitants, with up a third of its total residents being injured (Chester, 2001). Surprisingly in view of its proximity to the epicentre, the mortality figure of 1,020 for the Algarve represents less than 1.5% of the population of the region (Costa *et at.*, 2005). In 1755 the major population clusters in the Algarve were small and most people lived in single storey buildings that could be easily and quickly evacuated. Even in the principal settlements there were few deaths. For example: Tavira 10,436 inhabitants, mortality less than 1%; Faro 6,288 inhabitants, mortality ~3% and Loule 5,205 inhabitants, mortality less than 1%. For reasons that remain observe, the highest proportional mortality occurred in the village of Boliqueime (Fig. 2) which was totally destroyed necessitating its subsequent re-building on a new site (Fonseca, 2005), but even here mortality was only ~5% of the population. Many settlements recorded no deaths (Costa *et al.*, 2005, pp. 44).

The cost of the earthquake was very high. As expressed as a percentage of the national income of Portugal at the time as measured by its Gross Domestic Product (GDP), the cost is estimated at between 32 and 48% (Pereira, 2006), these figures being far higher than those recorded for most recent disasters in economically less developed countries (Benson, 1998). In fact and with only one exception, the GDP cost for Portugal in 1755 was higher than those recalled for countries affected by the 2004 Indian Ocean earthquake and tsunami. The Maldives had an estimated GDP cost of over 65%, but no other country had losses exceeding 6% although some regions close to the epicentre - such as Bande Ache in Indonesia - had figures even surpassing the figure for the Maldives (Shepard, 2005). Financial losses for the Algarve region have never been quantified, but in view of catastrophic character of damage discussed in this paper, must have been well in excess of the figure for Portugal as a whole.

The 1755 earthquake has been studied from many perspectives and has generated a vast literature on topics as diverse as theology and philosophy, art, literature, post-disaster planning and applied seismology. The earthquake struck on the morning of All Saints' Day (2 November) and in Lisbon and elsewhere many people were killed in church by falling masonry, with much devastation being caused by fires kindled by altar candles. This led many commentators at the time to ascribe the earthquake to divine wrath visited on the sinful people of Portugal, the group singled out for particular opprobrium being the people the writer wished to blame. For example one Portuguese Jesuit claimed it was punishment for the excessive 'leniency' shown by the Inquisition, whilst writing from the safety of England and from a Protestant perspective John Wesley blamed the disaster on the Inquisition's excesses. Voltaire's poem *Le desastre de Lisbonne* and more famously his novella *Candide* insisted that evil is a reality in the world. Dr Pangloss, who was Candide's tutor, accepts the fate of Nature even when faced with complete havoc, a view strongly challenged at the time by Jean-Jacques Rousseau (Basnett, 2006, pp. 323) who was a pioneer in defining the disaster as a 'social construct'; involving an interaction between the earthquake and a vulnerable human population (Dynes, 2000). In Portugal the most influential figure to hold views similar to Rousseau was the Marquês de Pombal, the King's powerful Chief Minister and the politician chiefly responsible for leading the nation as it put into place plans for recovery which most famously included the rebuilding of Lisbon in a grand style (França, 1977). Further information on these aspects of human responses to and recovery from the disaster may be found in: Chester (2001); Dynes (2005); Jack (2005) and Pereira (2006).

Until the last few years the impact of the *Lisbon earthquake* on the Algarve has not been the subject of detailed research, despite this being the area of Portugal lying closest to the earthquake's epicentre (Fig. 1) and the one most severely damaged. At the time of the earthquake and for more than two centuries following it, the Algarve was a remote region with an economy based on fishing and subsistence agriculture and one whose concerns were marginal to those of the nation as a whole (Wuerpel, 1974). This explains in part why the effects of the 1755 earthquake on the Algarve have remained under-researched, but another reason is related to the perceived paucity of data. Between 1919 and 1932, the *Serviços Geológicos de Portugal* published a monumental four volume work on the effects of the 1755 earthquake in Portugal (Pereira de Sousa, 1919-1932). Although making use of many historical sources, including a document known as the *Parochial Report* (also known as the *Dictionário Geográfico* or Geographical Dictionary - Tedim Pedrosa and Conçalves, 2008), that was based on a survey of parish priests carried out in 1758, Pereira de Sousa focused his research on an earlier survey that he discovered in the Portuguese national archives and which was distributed to parish priests immediately following the earthquake. Termed the *Marquis of Pombal's Survey*, the results for the Algarve have never been discovered with the result that in Pereira de Sousa's report there is far less detail on this region in than it deserves in view of the impact the earthquake had upon it (Fonseca, 2005).

From the 1970s, the economic fortunes of the Algarve were transformed and today the region is a major growth point within the Portuguese economy. The Algarve is the principal tourist destination within Portugal, receives c.42% of all tourist arrivals and accounts for 1.1% of global tourist demand, with over 600,000 visiting the region from the United Kingdom alone (Correia and Crouch, 2004). The population of the Algarve has risen from just under 267,000 in 1970 to over 400, 000 in 2001, a figure which includes many foreign expatriates but excludes holiday makers who visit mainly - though not exclusively - in the summer months (INEP, 2002). Today the region is highly exposed to the probable effects of future earthquakes and over the past few years there has been an intensification of research into the impact of the 1755 event and the lessons it may hold for emergency planning.

To mark the 250th anniversary of the earthquake in 2005 a group of Portuguese scholars published an authoritative survey of the effects of the 1755 events on the Algarve (Costa *et al*. 2005). Entitled, *1755-Terramoto no Algarve,* it not only makes extensive use of the *Parochial Report* but also brings together for the first time many additional contemporary documents written principally though not exclusively in Portuguese. Although *1755-Terramoto no Algarve* is a starting point for any study of the impact of the 1755 earthquake in the Algarve, additional information is reported in this paper and allows three aspects of the disaster to be brought into focus: its impact; the ways in which the region recovered following the disaster and the lessons this devastating event may hold for the future.

B. EARTHQUAKE IMPACT

Table 1 summarises the damage caused by the earthquake to the principal settlements of the Algarve and relates this to the *EMS-98 Intensity* scale (see Grünthal, 1998, pp. 99

and glossary). Figure 2 is constructed using information in the table together with additional data from the sources cited therein. The general pattern of losses in the Algarve is straightforward with almost complete devastation occurring closest to the most commonly proposed epicentre to the south west of Lagos (Fig. 1), and a rapid attenuation (i.e. decrease in intensity with distance – see glossary) towards the north east (Fig. 2).

Two additional points emerge. The first concerns the interpretation of the isoseismal lines plotted in Figure 2, since there are severe methodological problems involved in using historical data to estimate intensity (see Grünthal 2005, pp. 50-54). Information on the damage caused to each settlement, the data upon which intensity values are assigned (see glossary), is very variable both in quantity and quality. For some towns and villages there are comprehensive accounts, but for others there are few if any records (Table 1). Additionally the destruction caused to more substantial buildings owned by private individuals, the Church and the State is frequently over-represented in the archives, in contrast to that inflicted on more modest peasant and/or artisan dwellings (Martínez-Solares and López-Arroyo, 2004). In the case of the *Parochial Survey* this problem is probably exacerbated because its respondents were parish priests.

In the majority of historical earthquakes data are insufficiently detailed to allow Intensities X and XI to be differentiated (Grünthal, 2005), but on the basis the descriptions of damage (Table 1) a good case may be made for assigning an intensity of XI to an area west of Lagos. In Fig. 2 a zone of Intensity X and greater is recognised with confidence, whereas a zone exceeding of Intensity XI is plotted as a possibility. It is because of the configuration of the Algarve, its location with respect to the more likely locations of the earthquake epicentre (Figs. 1 and 2) and the resulting shape of the isoseismal lines, that attenuation (see glossary) is particularly marked along the southern coast of the Algarve. In their detailed studies of the effects of the 1755 earthquake in southern Spain (Fig. 2), Martínez-Solares and López-Arroyo (1999, 2004) classify buildings into two classes:

Type 1 - traditional masonry one and two storey buildings constructed in stone, brick and rubble; and,

Type II - structurally more complex and higher churches, castles and monasteries.

Damage to *Type II* buildings is much more common in Spain, some areas of which are located hundred of kilometres from the earthquake epicentre. Here ground motions have a pronounced low frequency component, which is known to exact a more severe toll on tall, structurally complex buildings (see glossary). *Type II* buildings also suffered major losses in Lisbon (Chester, 2001). A similar classification of buildings may be used the Algarve where it is notable that, whereas in settlements closest to the epicentre such as Sagres, Vila do Bispo and Lagos destruction is almost total and independent of building type, a more typically 'Spanish' pattern of losses is to be found at increasing distances; for instance in Olhão and Tavira (Table 1 and references). In Tavira many public and ecclesiastical building were lost, but people living in *Type I* housing were able to manage better than those in many other towns located nearer to the epicentre (Stanislawski, 1963, pp. 132-33; Serrao, 2001).

A second point about losses concerns possible interactions between the earthquake, buildings and surficial geology. Following the Mexico City earthquake of 1985, intense research was conducted into *three-way harmonic interaction* (Degg, 1992; 1995 – and see glossary), which involved the resonance coupling of earthquake waves, lake-bed deposits and medium to high rise buildings; the vulnerability of structures being enhanced when the natural frequencies of vibration of sub-soil conditions and buildings coincided. Many of the world's major cities are located on unconsolidated, often water-saturated sediments associated with river valleys and coastal plains, and in 1755 *three-way harmonic interaction* was clearly an important factor in determining the spatial pattern of damage in Lisbon where the greatest losses occurred on and near to the waterfront (Chester, 2001, pp. 375). In Spain far more damage was recorded when buildings were located on unconsolidated sub-soils (Martínez-Solares and López-Arroyo, 2004). The city of Lisbon is located over 300 km from the earthquake epicentre, 'low earthquake frequencies' predominated and 'low frequency' structures (e.g. large palaces and tall buildings) were particularly badly affected (Chester, 2001 and see glossary).

In the Algarve *three-way harmonic interaction* was probably a feature of the disaster because particularly near to the coast there are many outcrops of Pleistocene and Holocene weakly consolidated sands and unconsolidated alluvium, beach deposits and sand dunes (Fig. 2). In Tavira it is known that those areas of the town closest to the coast and located on river sediments and other unconsolidated deposits, were more seriously damaged than those positioned further inland on outcrops of 'hard' limestone (Costa, *et al*, 2005, Serrao, 2001). In contrast Faro, which is located only 29km form Tavira, was very badly damaged (Table 1) and it is notable that the city is built almost entirely on Pleistocene and Holocene deposits (Chester, 2001, pp. 376).

In the coastal zone of southern Spain processes of *liquefaction* (see glossary) were also noted in fine-grained unconsolidated sediments (Martínez-Solares and López-Arroyo, 2004) and it seems highly probable that this must also have occurred in the Algarve, although there is no specific mention of this in the historical record. The possibility of processes of both *three-way* *harmonic interaction* and *liquifaction* occurring in future earthquakes has major present-day planning implications (see below).

C. TSUNAMI IMPACT

Out of a total of 1,020 people who perished in the Algarve at least 440 were killed by the tsunami[1] (Costa *et al.,* 2005, pp. 44). Tsunamis may be generated by a number of mechanisms which in addition to earthquakes include: volcanic eruptions; volcano collapses - particularly of parts of volcanic islands into the ocean; landslides into the sea and catastrophic submarine mass-movements (Dawson, 1996). Despite the devastation wrought by the tsunami of 1755 it was towards the lower end of the magnitude range for tsunamis that can be generated in the Atlantic Ocean. The collapse into the ocean of a sector of one of its many volcanic islands would generate far larger tsunamis (Anon, 2003a). Reconstruction of the effects of historic tsunamis is a relatively new field of research (Dawson, 1999), which in the Algarve has been associated not only with assessing damage caused to coastal settlements, but also with using tsunami data to constrain models of earthquake generation and epicentral location (Chester, 2001, Bapista *et al.*, 2003). When reconstructing the 1755 tsunami similar historical sources to those used for evaluating the impact of the earthquake are employed, to which may be added information gleaned from historical cartography (Andrade, 1992; Andrade *et al.*, 2004; Costa, *et al.*, 2005). The evidence of sediments is important because tsunamis leave depositional records that contain valuable clues to the extent and impact of this most destructive coastal process.

Tsunami deposits from the 1755 tsunami have been identified as far away as eastern Scotland (Dawson *et al.*, 1991) and in the Algarve have been studied at several sites, the most well

[1] To this should be added many of those killed by the earthquake and tsunami in Lagos. An overall figure of *c.* 200 is often quoted for deaths from the earthquake and the tsunami (Costa *et al.*, 2005).

researched being the low-lying coastal inlet at Boca do Rio to the west of Lagos (Fig. 2). Here evidence shows that the tsunami was very destructive, with a core recovered from the area revealing that sediment representing 7-800 years of deposition had been eroded (Allen, 2003, pp. 269). At the same site Dawson *et al.*, (1995) and Hindson and Andrade (1999) concluded that the tsunami:

a. caused both erosion and deposition;

b. did not transport significant quantities of sediment from the offshore zone, but merely re-deposited material from beaches and dunes with shell debris and marine macrofossils being incorporated along with soils, estuarine silts and clays; and

c. involved the rapid deposition of chaotic mixtures of sediments of differing grain sizes.

The most important finding from Boca do Rio is that the upper height limits of sedimentation are lower than the run-up heights recorded in reliable historical documents, indicating that sediments cannot be used on their own to infer either the coastal impact or inland penetration of a tsunami, a finding which has major implications for hazard planning both in Portugal and elsewhere. Although the Boca do Rio has been the focus of study, tsunami sediments have also been been recognised elsewhere in the Algarve; for instance in the Alvor estuary (Fig. 2 and Table 2) by researchers from the University of Liverpool.

Sediments are not the sole manifestation of the 1755 tsunami and major impacts on coastal landscapes and settlements are summarised in Table 2. Although estimates vary (Tedim-Pedrosa and Conçalves, 2008), tsunamis took between *c.*16 and *c.*30 minutes to reach different parts of the Algarve and run-up heights, whilst declining overall at increasing distances from the epicentre, do not show a regular decrease. This was not only due to local geomorphological factors - in particular the shape of the coast and offshore bathymetry - but also to the state of the tide (Andrade, 1992; Mendes *et al.*, 1999, pp. 141). The tsunami reached the Algarve at low tide and, as in the Bay of

Cadiz in southern Spain where maximum run-up heights varied from 11-20m (Martínez-Solares *et al.,* 1979), occupied a considerable height range. Estimates differ and Kozák *et al*., (2005, pp. 38) quote maximum elevations of 30m at Sagres and Alvor, 12m at Quarteira and 4m at Portimão. More recently a detailed reconstruction has suggested a general height for the southwest part of the Algarve of 10-15m, a figure of *c*.20m at Alvor and a slightly lower inundation - 12m or slightly higher- at Portimão (Tedim-Pedrosa and Conçalves, 2008: pp. 61).

In places tsunamis penetrated a considerable distance inland, with figures of 2.5km being quoted for Lagos and Armação. Waves must also have travelled up the Guadiana valley which marks the border between Spain and Portugal, since both Castro Marim and Ayamonte (Fig. 2) were badly affected. The stagnant, pestilential and malarial character of the Rio Arade at Silves in the late eighteenth and early nineteenth century is noted by several contemporary writers and may have been due in part to sediments brought up the river by the tsunami, though long-term siltation produced by human-induced erosion within the river's catchment was probably a more important factor (Chester and James 1999).

C. RECOVERY

Immediately following the earthquake many people in the Algarve were rendered homeless and reduced to 'living in the fields' (Anon, 1755, pp. 563). For months and in some cases years after the earthquake the outputs of the region's fishing and handicraft industries were greatly reduced, but because the Algarvian economy was dominated by subsistence agriculture food continued to be produced. With the exception of ground covered by tsunami deposits and ruined buildings, land is not sterilised by an earthquake as is often the case following volcanic eruptions, flooding and landslides. There was no evidence of starvation and population figures - though fragmentary (Santos, 2001) - show only two instances of *concelhos*[2] (Portimão and Monchique) in which population was marginally lower in 1758 than it was in 1756. Whether rates of population increase were depressed for some time after the earthquake cannot be determined with any certainty, but there is some evidence of increased migration from the region. By the middle of the eighteenth century migration to other areas of Portugal, Spain and Gibraltar was already a long-established feature of the demography of the Algarve, with agricultural workers and fishermen frequently supplemented their incomes by spending time away from the region. Following the earthquake there is some evidence that the quantity and duration of migration increased. Portuguese predominantly from the Algarve comprised, for example, only 2% of Gibraltar's population in 1753, but this rose to 20% in 1814 (Borges, 2000).

According to Fonseca (2005), the 1755 earthquake was the first disaster in which the State assumed responsibility for a planned co-ordinated response. Immediately following the earthquake the Marqués de Pombal sent troops to the Algarve to prevent African pirates taking advantage of the trade opportunities afforded by the reconstruction of the region (Dynes, 2005, pp. 41). More substantial initiatives soon followed (Jorge *et al*., 2005). In the Algarve Pombal nationalised the catching, salting and trading of sardines, as part of a programme called the *Restaurção do Reino do Algarve* (Restoration of the Kingdom of the Algarve), which also involved the establishment of artisan-based industries and the building in 1773/4 of a new town, Vila Real de Santo António, facing the Spanish border (Fig 2). Relations with Spain were particularly strained in the 1750s

[2] The *concelho* is the primary administrative division within Portugal. Concelhos are divided into *freguesias* (i.e. parishes).

because of border disputes in South America and conflicts over fishing in home waters and the new town met a strategic as well as a development need. Vila Real was built in just a few months, was laid out on a grid pattern around a central square, made use of pre-fabricated units brought to the site by ship and adopted many of the earthquake-proofing techniques used successfully in Lisbon (Silveira *et al.* 2007). These including the use of a pioneering wooden anti-seismic frame, or *gaiola* (cage), built into the outer walls of major buildings (Tobriner, 1980).

Despite the best efforts of the Marquês de Pombal and his government, it took many decades for Lisbon and southern Portugal fully to recover from the effects of the earthquake. Indeed some suburbs of Faro were still ruined in the early years of the twentieth century and it was only with the development of industries involving the export of cork and canned fish, particularly sardines, in the nineteenth century that Lagos, Portimão, Silves and Faro regained their prosperity. Temporary affluence returned more quickly to Tavira because it was less badly damaged than other major settlements. It became the capital and principal city of the Algarve until it lost this status to Faro following nineteenth century administrative changes. Even in Tavira full recovery had to wait until the expansion of the fish exporting industries in the late nineteenth century (Stanislawski, 1963; Serrao, 2001; Garcia-Domingues, 2002; Jorge *et al*., 2005).

In the eighteenth century, Portugal could neither feed nor clothe her population entirely from her own resources, but before 1755 was able to pay for imports with wealth generated from her seaborne empire – particularly from Brazil, trade being largely under the control of British merchants. Despite an additional 4% tax levied on manufactured goods and merchandise (Marques, 1976, pp. 389-92), recovery costs were huge and beyond the resources of Portugal which until the second half of the twentieth century remained a country whose economy was based largely on subsistence agriculture and fishing. Reconstruction coincided with a fall in gold remittances from the empire and increased payments of bullion and diamonds to Great Britain and other European counties to pay for the increased imports required for the recovery programme (Boxer, 1956; Pereira, 2006).

D. CONCLUSION: THE LESSONS OF 1755

The 1755 earthquake was not an isolated incident and over the past thirty years great advances have been made in reconstructing the effects of other earthquakes and tsunamis that have affected the Algarve. Detailed archival research has shown that earthquakes causing major damage in the Algarve occurred in: 63BC (epicentre south west of Cabo do S. Vicente - magnitude *c*.8.5); 47BC (epicentre unknown - magnitude *c*.8.5); 33 BC (epicentre unknown - magnitude *c*.9.0); 309AD (epicentre west of Cabo do S. Vicente - magnitude *c*.7.0); 382 (epicentre south west of Cabo do S. Vicente - magnitude *c*.7.5); 1309 (epicentre west of Cabo do S. Vicente - magnitude *c*.7.0); 1353 (epicentre Silves - magnitude *c*.6.0); 1356 (epicentre south west of Cabo do S. Vicente - magnitude *c*.7.5); 1504 (epicentre near Carmona, Sevilha, Spain - magnitude *c*.7.0); 1531 (epicentre Vale de Tejo near to Lisbon - magnitude *c*.7.1); 1587 (epicentre near to Loulé - magnitude *c*.6.0); 1719 (epicentre near to Portimão - magnitude *c*.7.0); and 1722 (epicentre near to Tavira - magnitude *c*.7.0) (Oliveira, 1986; Martins and Mendes-Victor, 2001; Costa *et al*., 2005). Large earthquakes adversely affecting the Algarve have occurred since 1755 and these have not only occurred within the region but also in other areas of Iberia and north Africa. Their epicentres are mapped in Figure 3.

This long time-series of events stretching back more than 2,000 years has allowed estimates of the future recurrence of earthquakes of varying sizes to be calculated. The *World Map of Natural Hazards* (Munich Re., 1998), for instance, estimates that in the Algarve there is a probability exceeding 10% in 50 years (equivalent to a 'return period' of 475 years) that an earthquake of Intensity of VIII will occur. A magnitude 8.5 (M_w) earthquake (estimated return period 614±105 years), similar in size to 1755 and with an epicentre off the south west coast is taken by Portuguese geophysicists as the *worse-case future scenario* for the Algarve (Mendes-Victor *et al.* 1994, pp. 269, although uncertainty regarding the positions of the epicentres of high magnitude earthquakes (Fig. 1 and references) means that the return period of an 8.5 M_w event may be *c.*1,000 years (Tedim-Pedrosa and Conçalves, 2008, pp. 62).

Following the 1755 earthquake, Portugal became one of the first countries in the world to introduce codes of good practice for buildings in seismically active zones. When reconstructing Lisbon the Marquês da Pombal and his principal architect, General Manuel da Maia, demanded that:

a. building heights should be restricted;

b. streets must be a minimum width;

c. architectural ornamentation should be kept to a minimal and

d. fire breaks between the roofs of adjacent building must be introduced.

These features were also incorporated into the design of Vila Real de Santo Antonio and many post-1755 buildings in other towns and cities in the Algarve, and remained standard practice in Portugal until the 1920s (Tobriner, 1980; Chester, 2001). As late as the 1980s revision of building codes dominated hazard planning (Oliveira and Pais, 1995), but the Azores earthquake of 1980 which killed 60 people and rendered *c*.22, 000 homeless, highlighted a major problem with this approach. Whereas reinforced concrete buildings constructed to the most recent earthquake codes performing well, *c*.90% of traditional masonry buildings were destroyed (Carvalho, 1980; Degg and Doornkamp, 1994), these being similar to the *Type 1* buildings adversely affected by the 1755 earthquake especially near to its epicentre (Martinez-Solares and Lopez-Arroyo 1999, 2004). Although there is some anecdotal evidence to suggest that enforcement of building standards in the Algarve was not all in might have been at the height of the building boom in the 1980s and early 1990s (Chester, 2001), experience of losses from the Azores earthquake is generally positive as far as the Algarve is concerned. Much of the tourist infrastructure and new housing comprises reinforced concrete buildings, similar to that which survived the 1980 Azores earthquake. *Type 1* construction; however, continue to dominate the historic cores of cities and town in the Algarve and virtually all the building stock within smaller villages is of this type.

What is required in the Algarve is more research which combines estimates of the recurrence intervals of earthquakes of differing magnitude with studies of geology, soil mechanisms and topography to produce detailed hazard maps. These can then be integrated into parallel surveys of buildings, demography and probable social impacts. For the Lisbon studies of this type have been published and are linked to civil defence planning (e.g. Mendes-Victor *et al*., 1994). The growing populations both resident in and visiting southern Portugal, the large number of hotels and other tourist-related buildings, the frequent occurrence of ‘soft’, sometimes water-saturated sediments - with the potential to induce *three-way harmonic interaction* and *liquifaction* - and the growing importance of the region within the Portuguese economy, means that there is a widely recognised need to develop similar integrated hazard studies in the Algarve (Anon, 2003b). One preliminary study addressing the above issues was undertaken in the early years of the present decade in the City of Faro, but it was admitted that more detailed studies were required both for Faro itself and the wider Algarve (Anon, 2004: 54). Another pioneer study has recently been published (Tedim-Pedrosa and Conçalves, 2008), in which the area of Portimão *concelho* that would be devastated by a *1755-type* tsunami has been calculated at nearly 24km^2, representing *c*.13% of its total area. The probable effects of a *1755-type* tsunami are mapped at a 1: 5,000 scale and the authors of the study estimate that over 18, 000 people would be adversely affected, together with 26 out of the 67 tourist hotels. For the Algarve these studies represent an excellent start, but similar studies in other *concelhos* are clearly required and in February 2008 it was announced that such a programme was to be undertaken (Anon, 2008). Called the *Estudo do Risco Sísmico e de Tsunamis para o Algarve* (Seismic Risk Study for the Algarve – ERSA), it aims to produce a comprehensive assessment of risk and create a detailed emergency plan for each *concelho* in the Algarve. At the press conference to launch the study it was stated that without preventative measures, a magnitude 8.5 earthquake could kill *c*.3,000 people in the Algarve and render *c*.27,000 homeless.

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TABLE AND FIGURE CAPTIONS

Table 1 Earthquake losses in the Algarve, related to the *EMS-98 intensity* scale (Grünthal, 1998). Damage to the principal town of each *concelho* (e.g. county) and other important settlements is listed. The effect of the earthquake on other settlements is discussed by Costa *et al.* (2005, pp. 91-92 and 113).

Table 2. Summary of the characteristics and effects of the 1755 tsunami on the Algarve coast (Based on information in: Pereira de Sousa, 1919-1932; Stanislawski, 1963; Andrade, 1992; Mader, 2001; Andrade *et al.*, 2004; Costa *et al.*, 2005; Fonseca, 2005; Kozak *et al.*, 2005; Anon, 2006 and the specific references quoted in the table).

Fig. 1. Isoseismal map of the 1 November 1755 earthquake (based on: Martínez-Solares 1979, 2004; Elmrabet, 1991; Levret, 1991; Degg and Doornkamp, 1994, pp. C2.5.12 and Chester, 2001).
There are several disputed tectonic origins for the 1755 earthquake. Until the late 1980s most

writers assumed that the epicentre was located on the *Gorringe Bank*, which was also associated with the 28 February 1969 earthquake. It now believed by most writers that the *Gorringe Bank* tectonic structure is incapable of producing a tsunami as large as that of 1755 (Costa *et al*. 2005, see also: Udias *et al.* 1976; Mendes *et al.* 1999; Borges *et al.* 2001). Other suggested origins include: a structure called the *Marque de Pombal Fault* (Zitellini et al. 2003; a composite source involving the *Marquis of Pombal Fault* and a structure known as the *Guadalquivir Bank* (Baptista et al. 2003); and most recently a subduction fault plane in the Gulf of Cadiz much further to the east (Gutscher, 2004). As Fonseca (2003) points out, placing the epicentre to the east makes it difficult to explain the observed patterns of intensity data and damage, which implies attenuation (see glossary) from an implied marine epicentre located to the south west of Portugal.

Fig. 2. Zones of differing *intensity (EMS-98)* for the 1755 earthquake in the Algarve (Grünthal, 1998). Based on information in Table 1 and other sources.

Fig. 3. Epicentres of major earthquakes in Iberia: 1500-1980AD. Based on information in Degg and Doornkamp (1994, pp. C2.5.8) and used with permission.

Table 1

***EMS-98* Intensity**	**Definition**	**Description**[1]	**Effects of the earthquake on the principal town or city of each *concelho* (e.g. county) and other important settlements**[2] Within each row, settlements are listed at increasing distance from an assumed epicentre on the Gorringe Bank.
Greater than XI			**Sagres** - All houses were destroyed. With the exception of the walls of the fortress, all other substantial State, religious and private buildings were either severely or badly damaged. **Vila do Bispo** - only one building remained after the earthquake.
XI	Devastating	Most ordinary	

	well-built buildings collapse	
X-XI		**Luz** - Fort and bell tower unaffected, but other chapels destroyed. **Lagos** - Many State, Church and substantial private buildings were totally destroyed. These included: over 12 major religious buildings; the town hall; the jail and most of the housing. Nearly all other religious buildings and all the remaining houses were severely damaged. **Aljezur** - The castle, the parish church and many houses were totally destroyed. Virtually all remaining houses were severely damaged. **Alvor** - The bell tower of the church and 12 houses were totally destroyed, the castle and the parish church were severely damaged and most religious buildings showed some signs of damage. **Portimão** (then known as Vila Nova de Portimão) - 200 houses, the parish church and several religious buildings were totally destroyed, with many others being either severely or partially damaged. **Lagoa** - The parish church, a fort, a major convent and many houses were destroyed. The majority of the houses and other religious buildings were severely damaged. **Silves** - The castle walls, cathedral, town hall, other public buildings and most of the houses were totally destroyed. The remaining houses were damaged. **Albufeira** - The parish church and many houses were totally destroyed.

			Boliqueime - Settlement entirely destroyed.
			Loule - Nearly all the housing and 7 major churches and the jail were totally destroyed. Three other churches were severely damaged, together with the tower in the Castle and the remaining housing.
			Faro – The Cathedral, the Bishop's palace and 8 major religious buildings (most within the historic core) were destroyed, together with more than 600 houses. The Fortress walls and a further church were severely damaged.
X	Very Destructive	Many ordinary well built buildings collapse	
IX-X			**Monchique -** The convent was totally destroyed, most of the other religious buildings were severely damaged. The the majority of houses suffered only minor damage.
			Olhão – The church tower was totally destoyed, the *Templos* (temple) and most houses were damaged. Overall Olhão was one of the least badly affected settlements (Pereira da Sousa, 1919-32).
			São Brãs de Alportel - Parish church damaged no other details are available.
			Tavira – The church hospital, some religious buildings and houses near to the river were destroyed. Other religious buildings were severely damaged and many houses survived. Not as badly damaged as Lagos and Faro, the other major settlements of the Algarve.
IX	Destructive	General panic. Many weak constructions	

		collapse. Even well built ordinary buildings show very heavy damage: serious failure of walls and partial structural failure	
VIII-IX			**Castro Marim -** The parish church, the fort, the bullring and the Governor's house were all destroyed. No other damage is listed in the sources. **Alcoutim -** No information is available from the sources. **Vila Real de Santo Antonio** - Built as a new town following the earthquake.
VIII	Highly damaging	Many people find it difficult to stand, Many houses have large cracks in their walls. A few well built ordinary buildings show serious failure of walls, while weak older structures may collapse.	

[1] Descriptions are from the 'short form' of *EMS-98*. The zoning used in Figure 2 is based on the more comprehensive definitions (see Grünthal, 1998, pp. 99). [2] Based on Costa *et al.*, 2005, with additional information in: Stanislawski, 1963; Brooks, 1994; Garcia-Domingues, 2002; Paula, 2001; Santos, 2001 and Serrao, 2001.

Table 2

	Details
Attributes	Following the earthquake, the tsunami took 16 minutes to travel to Cabo do S. Vicente and 30 minutes to reach the Spanish border. Lisbon was affected 30 minutes after the earthquake, the Gulf of Cadiz after 30-78 minutes (estimates vary), Madeira after 90 minutes and Martinique after *c*.600 minutes. Run up heights varied from 11 to 30m according to some sources, although the latter figure may be exaggerated. A maximum height of 13m - 20m may be more realistic for the Algarve.
Area affected	
Cabo do S. Vicente to Lagos	Sagres - was destroyed by what some sources claim was a wave 30m height, though this may be an exaggeration. At Martinhal beach there was a marine incursion of *c*.2km and blocks weighing *c*. 4,500kg were deposited (Silva-Lopes, 1841; Kortekaas and Dawson, 2007, pp. 211). Lagos - the walls of the town, a church, two fortresses and many houses were virtually destroyed. Around 3% of the population

	was killed by the earthquake and tsunami. The fortress of Maia Praia was 'cut in two' and some sources claim that the sea penetrated 2.5 km inland. The harbour was choked with sediment.
Lagos to Portimão	Alvor - Fishermen were swept from the beach. Before 1755 the harbour could accommodate ships up to 45 tonnes. After the earthquake only small craft could be handled. Inundation spread 600m inland and destroyed buildings on land up to 30m in height. The chapel of Nossa Senhora da Ajuda located on the beach was totally destroyed (Silva-Lopes, 1841; Tedim-Pedrosa and Conçalves, 2008). Portimão - The walls and fortifications of the town were destroyed or severely damaged, together with some of the suburban housing and a major fortress. Many houses within the town were badly damaged and 46 people were killed, 6 being killed by the earlier earthquake. Inundation reached 880m inland, and spread 5km up the Rio Arade. Some 13% of the *concelho* was flooded. Waves at the coast may have been *c*.20m at Alvor and somewhat lower at Portimão (Tedim-Pedrosa and Conçalves, 2008)
Portimão to Albufeira	In Albufeira and Quarteira there were many changes of ground level, producing areas where drainage was impeded. Stagnant pools, which frequently became malarial, were formed and sand accumulated. Armacão de Pêra - A fortress, the church and around half the housing was destroyed, with much of the rest being badly damaged. 67 people were killed in the town and surrounding area. Albufeira - Virtually all the low lying Santa Ana district was destroyed. Many people sheltered on the beach following the earthquake and perished in the subsequent tsunami.
Albufeira to Faro	Quarteira - Some fisherman's cabins were destroyed. Faro - The city was largely protected by the Rio Formosa Barrier System, but historical cartography (Andrade, 1992; Andrade *et al.*, 2004) shows that the tsunami caused major changes to the offshore islands. Several rivers were choked with sediment, adversely affecting their navigability.
Faro to Castro Marim	All the fisherman's cabins were destroyed in Monte Gordo**,** together with and some houses in Castro Marim. Near to the mouth of the Rio Guadiana, increased erosion occurred and

eventually the settlement of Santo António de Arenilha was washed away. In Cacela Velha the former Islamic castle was destroyed.

GLOSSARY

Attenuation is the decrease in intensity of ground shaking with distance from the source of the earthquake.

Intensity provides a descriptive assessment of the size of an earthquake, based on its impact on people, buildings and the ground surface. Isoseismal lines represent equal earthquake intensity. There are a number of intensity scales: including the *Modified Mercalli (MM)*, that is the world standard; and the *Medvedev-Sponheuer-Kárnik (MSK)*, which has traditionally been used by European seismologists. A new scale more suitable for use in Europe was published in 1998. It is known as the *European Macroseismic Scale 1998 (EMS 98)* (details are available from http://www.gfz-potsdam.de/pb5/pb53/projekt/ems/), is the current European standard and is virtually identical to the *MSK* scale. Although differing in detail, the *MM*, *MSK* and *EMS 98* scales are broadly similar. All three scales run from I (minimum) to XII (maximum). Because they are descriptive and based on recorded damage, intensity values may be calculated and isoseismal lines drawn for both present day and historic earthquakes, allowing comparisons to be made. Recent papers have demonstrated ways in which intensity may be calculated using the effects of palaeoseismicity on the environment (e.g. liquefaction, rockfalls and ground fissures)

(Fokaefs and Papadopoulos, 2007; Papathanassiou and Pavlides, 2007).

Liquifaction (also Liquefaction) is a condition of fine-grained saturated soils and unconsolidated sediments. When subject to repeated shaking 'the pressure of water between the sand grains increases until eventually the sediment takes on the character of a dense liquid rather than that of a solid' (Bolt, 1999, pp. 236).

Low and high frequency structures. In Lisbon, Spain and the eastern Algarve, damage to low frequency structures (e.g. large palaces and high complex buildings), was significantly greater than that to 'high frequency' structures (e.g. 'stiff' buildings such as small chapels and low-rise houses with simple square or rectangular shapes) (Oliveira, 1986). The reasons were twofold. First, damage in earthquakes is inversely correlated with building stiffness and many buildings in Lisbon and elsewhere had little resistance to horizontal shearing (Tiedemann, 1992: 350-351) and, secondly, high frequencies are more rapidly attenuated than low frequencies at increasing distances from the epicentre. In the Lisbon, located ~300-350km from the epicentre, low frequencies predominated (Mendes-Victor, 1987) as they did in Spain and the eastern Algarve.

Magnitude is a quantitative measure of the amount of energy released by an earthquake. Because they are based on seismographs, magnitude values have only been available for just over 100 years, but may be estimated from intensity measurements. Traditionally a scale devised by Charles Richter in 1931 and known as the Richter (or local) magnitude (M_L) has been used. For each unit increase in magnitude, the amplitude of seismic waves increases 10 times and the energy released about 30 times (e.g. a magnitude 8.6 event releases almost 1 million times more energy than a magnitude 4.3 event). Other magnitude scales include: the surface wave magnitude (M_S) and the moment magnitude (M_W). Based on information in Bolt (1999).