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The impact of eighteenth century earthquakes on the Algarve region, southern Portugal

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In the eighteenth century the Algarve was affected by two large and destructive earthquakes. The first occurred in 1722, had an estimated magnitude of between 6.5 and 7.8 M_w and severely affected the coastal zone of the central Algarve. Thirty three years later in 1755 the 'Lisbon earthquake' (magnitude *c.* 8.5 M_w) killed around 12 000 people in Portugal, of whom just over 1000 lived in the Algarve. With an estimated cost of between 32 and 48% of Portugal's gross national product, in financial terms it is the greatest natural disaster to have affected western Europe and its effects on the Algarve, the region closest to the epicentre, were devastating. Using data collected in the field together with archival materials the authors discuss: the economic and social impacts of these two eighteenth century earthquakes and their associated tsunamis on the Algarve; and recovery of the region in the years that followed. Today the Algarve is a major European tourist destination with a resident population of *c.*430 000, a figure which almost doubles at the height of the tourist season. The 1722 and 1755 earthquakes were not isolated events, but part of a long and destructive seismic history, and today the region is highly exposed to the effects of future earthquakes and tsunamis. The paper concludes with a discussion of current attempts being made by the Portuguese authorities to reduce hazard exposure by means of building codes, the production of hazard maps and emergency plans. In these plans a 1755 type event is viewed as a worst-case scenario, although because of its epicentral location near to the economic heart of the region and in spite of its smaller size, a 1722 type event would be far more destructive.

KEY WORDS: Algarve, 1755, Lisbon, earthquake, tsunami, hazard planning

Introduction

In the aftermath of the massive Indian Ocean earthquake and tsunami (moment magnitude M_W[1] 9.1), which occurred on 26 December 2004 and killed *c.* 230 000 people (Shepard 2005; USGS 2009), the inhabitants of many countries bordering the world's oceans became acutely aware of their exposure to hazards of this type, none more so than the Portuguese. In Portugal some programmes of scientific research were already in place (e.g. Mendes-Victor *et al*. 1994; Anon 2003; Blanc 2009), but these were given new impetus and urgency as a result of events in the Indian Ocean. In addition to mark the 250th anniversary of the Lisbon earthquake in 2005 many historically based investigations of earthquakes and tsunamis that had affected Portugal were undertaken (e.g. Fonseça 2005), which were subsequently used by hazard analysts to propose a number of future disaster scenarios (e.g. Mendes-Victor 2006; Rio *et al*. 2006; Baptista and Miranda 2009; Mendes-Victor *et al*. 2005 2009; Carvalho *et al*. 2008b).

In 1755 around one third of the buildings in Lisbon, the capital city of Portugal, were ruined by the earthquake and much of southern Iberia and north Africa were also laid waste, with the effects of associated tsunamis being felt – albeit with decreasing force – as far away as the UK and the Caribbean (Anon 2006; Chester 2008). The earthquake involved three main shocks and many aftershocks which lasted until 20 August 1756 and, although mortality estimates of up to 70,000 are often quoted (e.g. Bolt 2004: 305), these

are exaggerated (Chester 2008), with recent estimates based on more detailed historical research being more modest. For Portugal estimates of *c*.12 000 deaths from all causes (i.e. earthquake, tsunami and fire), with *c*.10 000 occurring in Lisbon are often quoted (Mendes-Victor *et al*. 2005; Chester 2008), although the most comprehensive survey to date suggests a mortality of 20–30 000 in Lisbon and combined deaths of 35–45 000 for Portugal, Spain and Morocco (Pereira 2009). Estimates of deaths in the Algarve vary from 1020 or 1038 (see Costa *et al*. 2005, 44) to up to 2000 (Pereira 2009) and in the Algarve virtually all deaths were caused either by building collapse, in the case of the earthquake, or from the effects of flooding, in the case of the tsunami, which probably claimed the lives of *c*.440 people (Costa *et al*. 2005, 42–4). The total direct cost of the disaster for Portugal, as measured as a percentage of its gross domestic product (GDP), have been estimated at 43–57% (Estorninho 1956), 75% (Cardosa 2007), 115–153% (França 1977) and 133–175% (Pereira 1953), largely because Portuguese GDP in the 1750s is poorly constrained (Pereira 2006). After careful discussion of these figures and using additional evidence, Pereira (2006 2009) provides an estimate of 32–48%, a figure which is still far higher than those cited in recent decades for most large-scale of disasters in economically less developed countries (Benson 1998). Indeed with the exception of the Maldives, which suffered an economic toll of *c*. 65% of its GDP, no other state affected by the 2004 Indian Ocean earthquake and tsunami had figures in excess of 6% of GDP, although some of the regions closest to the epicentre, such as Banda Aceh in Indonesia, suffered a far higher economic loss (Shepard 2005). In contrast to 1755, no major city was affected by the earthquake and tsunami of 2004, although the January 2010 Haitian earthquake which severely impacted the capital, Port-au-Prince, and devastated one of the *poorest* countries of the world, had estimated GDP costs of between 104 and 117%, which together with a death toll of *c*. 250 000 makes it one of the worst disasters ever to affect a single country (Anon 2010; Carvalho *et al*. 2010).

With the exception of its detailed impact on the Algarve, the 1755 earthquake is one of the most intensely studied historical disasters and has generated a vast literature on themes as diverse as philosophy and theology, post-disaster planning and applied seismology (Dynes 2000; Chester 2001; Poirier 2005; Araújo *et al*. 2007; Chester and Duncan 2009; Mendes-Victor *et al*. 2009). In 1755, Sebastião José de Carvalho e Melo, known to history by his later title of the *Marquês de Pombal*, was one of the King's principal ministers and skilful handling of the emergency consolidated his position (Pereira 2009). The national recovery programme Pombal put into place is best remembered for the re-building of Lisbon's ruined core in the grand eighteenth century style, which is known eponymously as Pombaline (França 1977), but he was also a critical figure in the reconstruction and economic recovery of the Algarve (see below). Considered by some writers to have been a benevolent dictator who rescued Portugal from both the spiritual oppression of church and Inquisition and the economic stranglehold of the nobility and Great Britain, Pombal was also known for corruption and the brutality of his regime (Francis 1985; Saraiva 1997; Cavendish 2001; Pereira 2006 2009).

The Algarve is the region of Portugal closest to the epicentre of the 1755 earthquake, and has been affected on at least 21 occasions by earthquakes[2], of which the 1722 and 1755[3,4] (Oliveira 1986) events were the most damaging. Despite this history of seismic activity, until recently little had been published on the impact of earthquakes and tsunamis on the Algarve. In the eighteenth century the Algarve was a remote region of peripheral concern to the Portuguese nation as a whole (Stanislawski 1963; Wuerpel 1974), but the principal reason why the effects of the large earthquakes of 1722 and 1755 were under-researched was the strongly held academic opinion that data were lacking. For many years the main source of information on the effects of the 1755 earthquake was *O Terremoto do 1º Novembro de 1755* (*The earthquake of November 1 1755*), published in four volumes by the *Serviços Geológicos de Portugal* between 1919 and 1932 (Pereira de Sousa 1932). Pereira de Sousa made use of a wide variety of historical sources, including a document entitled *Memórias Paroquiais* or the *Dictionário Geográfico* and usually known in English as the *Parochial Report* (Tedim Pedrosa and Conçalves 2008) and which resulted from a survey sent to parish priests in Portugal during 1758, but his work was primarily based on an earlier 1756 survey that he discovered in the national archives. This was again derived from written responses of priests who were surveyed immediately following the earthquake (Carneiro and Mota 2007) and is known as the *Marquês de Pombal's survey*. Returns for the Algarve and the Lower Tagus regions have, unfortunately, never been discovered (Fonseça 2005, 52)[5].

In order to mark the 250th anniversary of the 1755 event, in 2005 a group of Portuguese scholars published a comprehensive account, *1755 – Terramoto no Algarve* (*1755 – earthquake in the Algarve*) (Costa *et al*. 2005). *1755 – Terramoto no Algarve* brought together for the first time many contemporary and near contemporary source materials – both written and cartographic – the majority of which are in Portuguese, but the work focuses on the information contained in the *Parochial report*. The *Parochial report* comprised answers to three groups of questions concerned with the characteristics of the land (Part I – 27

questions), mountains (Part II – 12 questions) and rivers (Part III – 20 questions) within each *freguesia* (i.e. parish). For study of the impact of the 1755 earthquake the most important question is number 26 in Part I, which asks the parish priest 'if you suffered any ruin during the 1755 earthquake and where and whether this has been repaired?' (our translation). From a facsimile of the original document, Costa *et al*. (2005) not only reproduce the questions but also the answers to question 26 for those *freguesias* located in the Algarve.

For many years the only information available on the 1722 earthquake and tsunami was contained in a volume, *Historia Universal dos Terremotos* (*The universal history of earthquakes*) by Moreira de Mendonça (1758), who at the time of the earthquake worked in the National Archives at Torre do Tombo in Lisbon, and today the only original copies of his work are located in major research libraries, although a microfilm version is more widely available. *Historia Universal dos Terremotos* also contains useful information on the 1755 earthquake. Some but not all of the information compiled by Moreira de Mendonça is reproduced by Costa *et al*. (2005) and further sources of information on the 1722 event have been identified by Fonseça (2005), Baptista *et al*. (2007) and Baptista and Miranda (2009).

Whereas *Historia Universal dos Terremotos* and *1755 – Terramoto no Algarve* constitute a useful starting point for any study of the impact of the two eighteenth century earthquakes on the Algarve, in this paper we report additional information which has been collected through both field investigation and further bibliographic study. With regards to the latter, of particular value are local histories that are available from the libraries and archives of the 16 *concelhos* (i.e. counties) which constitute the Algarve (Figure 1). Using this material it is possible to bring three aspects of these two eighteenth century disasters into focus:

1 their impacts on the population and economy of the time;
2 the mechanisms by which the Algarve coped with and recovered from the disasters; and
3 the lessons these devastating events hold for future hazard planning.

The impact of the earthquakes and tsunamis

The Algarve in the early eighteenth century

In the early eighteenth century the Algarve was an isolated, subsistence-based agricultural region, far removed from the principal interests of the Portuguese State which were focused on central and northern Portugal in general and, more particularly, on Lisbon and the wealth derived from the country's burgeoning seaborne empire and foreign trade (Boxer 1969; Wuerpel 1974). From the eighth to the thirteenth century *CE* the Algarve was under the control of Moslem settlers who made Silves (Figure 1) their capital. They not only introduced citrus crops and irrigation, but were also responsible for forest clearance, especially on the hills to the north of the city, thereby inducing widespread erosion of topsoil and its deposition both within coastal estuaries and in the valleys of the south flowing rivers (Chester and James 1991 1999). From the start of the Christian re-conquest in the twelfth century, new settlers from regions to the north of the Algarve, existing Christians and Islamic converts to Christianity (known as *new Christians*), while maintaining irrigation and the cultivation of citrus fruits, developed an agricultural system of intercropping cereals, tree crops and vegetables that was little different from that found over much of central and northern Portugal (Stanislawski 1963, 10, 14). The focus of activity shifted southwards to the limestone

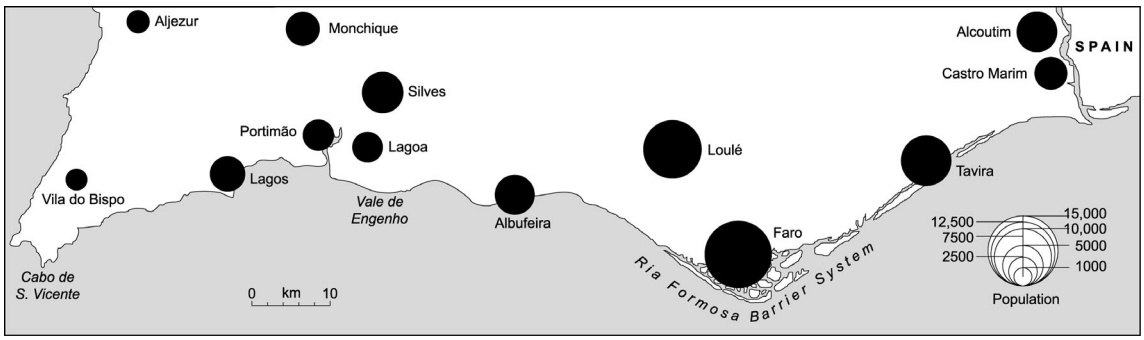

Figure 1 The principal settlements of the Algarve in the early eighteenth century. The figure shows the population numbers in 1732 plotted as proportional circles for the principal settlement of each *concelho*. Population numbers are taken from Silva-Lopes (1841). Figures for Aljezur are for 1756

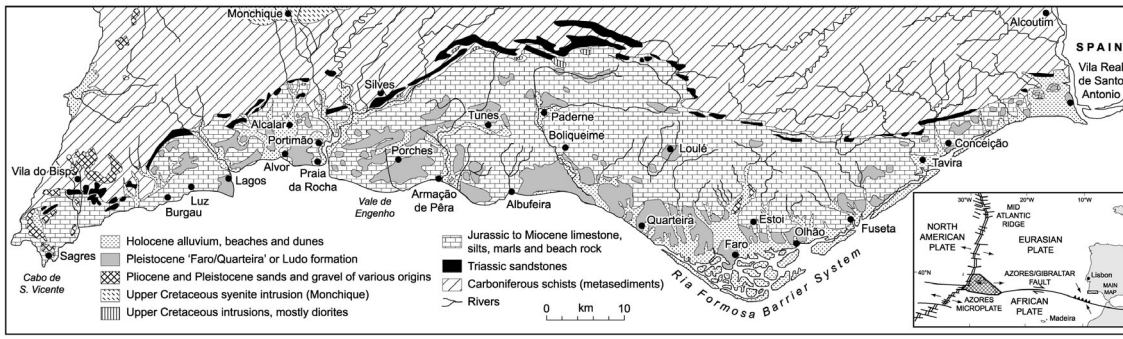

Figure 2 Simplified geology of the Algarve (information is from Chester and James 1999, 173, 174, Figures 2 and 3). Inset map shows the regional plate tectonic picture and plate boundaries (based on various sources)

belt (Figure 2), with the coastal lands maintaining the importance they had held since before Roman times. Not only did this system reduce erosion, because the easily eroded soils of the *metasediment hills* to the north of Silves (Figure 2) were less intensively exploited (Chester and James 1999), but population pressure was also not acute for many centuries. Despite the western Algarve, in particular the port of Lagos and the Sagres peninsula, being important during the Age of Discovery – especially following the appointment of Prince Henry the Navigator as Governor of the Algarve in 1419 – the long-term impact on the economy of the region was minimal (Figure 2). As Sir Charles Boxer (1969, 56) noted, the Algarve was not a particularly attractive region for new settlement and until the nineteenth century never possessed the population numbers the agricultural system and riches of the offshore fisheries were capable of supporting. In fact it has been noted that as late as the eighteenth century, the fisheries better served the interests of Spain than the Algarve (Costa *et al*. 2005, 39) and the northern boundary of the region with the rest of Portugal was treated as a border, with taxes being levied on imports and exports (Stanislawski 1963, 14). The *Mapa do Reino do Algarve* published in 1700 shows only three routes to the north: one along the west coast; and two from Silves and Tavira. Even the adjacent settlements of Faro and Tavira were not linked by a direct road (Costa *et al*. 2005, 29). As a consequence of poor inland communications the Algarve looked to the sea, exporting dried fruit, wine, olive oil and salted tuna and importing grain because the region was rarely self-sufficient in wheat (Costa *et al*. 2005, 29–39),

Notwithstanding these problems, in the 200 years leading up to the mid-eighteenth century some innovation and agricultural development took place, with maize being introduced from the New World (Mabberley and Placito 1993, 228), cork being exported to England for the first time and overseas trade being increasingly dominated by merchants from Great Britain, filling the place left by *new Christian* traders who were subject to severe persecution by the Inquisition (Costa *et al*. 2005, 37). Data compiled by Silva-Lopes (1841) and Magalhães (1999) show a population 63 682 for the Algarve as a whole in 1732: with Faro (13 577) being the most populous centre; followed by Loulé (10 245), the principal marketing town of the limestone belt; Tavira (7610); Silves (5117); Alcoutim (4905); Albufeira (4724) and Lagos (3713) (Figure 1). These figures reflect:

1 the long-term decline of Silves since Islamic times, due to a combination of a southwards shift in the focus of agricultural activity and siltation within the Arade Valley producing in its wake unhealthy, pestilential conditions within the city (Costa *et al*. 2005, 38);
2 the growth of coastal settlements, in particular Faro; and
3 the increasing importance of the major inland agricultural market towns of Loulé and Alcoutim (Figure 1).

In 1732 the Monchique, a syenite massif reaching to over 900 m in height (Figure 2), supported a population of 3413 and was the focus of a prosperous high-altitude well-watered and relatively prosperous region, in which agriculture geared to export was practiced in valley bottoms, with the forested slopes of the massif being exploited for chestnut wood, much of which was exported (Stanislawski 1960 1962).

Until the sixteenth century, when the Bishop moved to Faro, Silves was the capital of the Algarve and at the time of the 1722 earthquake Lagos was its seat of

government, although Faro was far more important in terms both of it population and trading position (Stanislawski 1963, 127–8) and acted as the *de facto* capital (Costa *et al*. 2005, 39).

The 1722 earthquake and tsunami

The earthquake of 27 December 1722 struck Tavira between 5 and 6 pm, was felt all over the Algarve and was quickly followed by a tsunami, which overtopped the cliffs along the Algarve coast and caused much damage in Tavira, Faro and other areas of the central and eastern Algarve (Figure 1)[6]. Although there are far fewer historical details available than for the 1755 earthquake, there being insufficient data to make either firm magnitude estimates – which vary from M_W 6.5 (Baptista *et al*. 2007) to M_W 7.8 (Almeida *et al*. 2006) – or to know how many people were killed and/or injured, what is known from the historical record indicates that this was a major event which had a significant impact on the economy of the Algarve (Figure 1). Using records of building damage (Table 1), it is possible to calculate earthquake intensity[7] and to construct an isoseismal map (Figure 3) of the earthquake which shows high intensity (values in excess of IX) in the Faro, Loulé and Tavira area, a projected epicentre just offshore, and rapid attenuation (i.e. decrease in ground shaking) in all directions from the epicentre.

In contrast to the 1755 disaster, destruction in 1722 was much smaller in scale, affected more restricted areas of the principal towns and cities located close to the epicentre (Figure 1) and, as far as can be determined from historical sources, reconstruction was largely complete in the 33 years which separate the two disasters. In fact some of the buildings destroyed or badly damaged in 1722 had clearly been repaired or rebuilt because they were destroyed or badly damaged once again in 1755. For example, Moreira de Mendonça (1758, 92, 156) records that the *Igreja do Colégio dos Jesuitas* (the church and college of the Jesuits) in Portimão was devastated in both 1722 and 1755. Furthermore in 1750 it was noted that a commemorative procession took place every year in Tavira on the anniversary of the disaster in order to keep its memory alive in the minds of the inhabitants (Belém 1750; Baptista *et al*. 2007, 374), implying that physical scars to the urban fabric, which would have acted as constant reminders of the earthquake, had largely healed.

Most historical earthquakes that affect the Algarve have epicentres located off the southwest coast and the 1722 event is important because it demonstrates that destructive earthquakes may originate in other areas, a finding that has major implications for present day hazard assessment (see below).

The impact of the 1755 earthquake

Table 2 is a summary of the damage caused by the 1755 earthquake to settlements in the Algarve. Using the data in Table 2 together with the sources cited, Figure 4a has been constructed by the authors to illustrate the pattern of isoseismal lines across the Algarve, while Figures 4b and 4c use the references cited respectively to show: isoseismals for the whole of Iberia and the adjacent regions of north Africa; and the tectonic setting of the earthquake.

The epicentre and source of the 1755 event is still a matter of fierce debate, which is far from being an arcane matter of historical geophysics because epicentral location strongly influences future hazard scenarios (see below). For many years it was assumed that the epicentre was located on or near to the *Gorringe Bank* tectonic structure (Udias *et al*. 1976; Johnston 1996), which was also associated with the 28 February 1969 earthquake (Figure 4b), but later a source to the north on the *Marques de Pombal Thrust* was proposed (Baptista *et al*. 1998a 1998b; Figure 4c). This suggested location and the *Gorringe Bank* source make it difficult to interpret the distribution of damage in north Africa in a consistent manner. Baptista *et al*. (2003) proposed a composite seismic mechanism involving both the *Marques de Pombal Thrust* and a fault segment on the southern flank of the *Guadalquivir Bank* (Figure 4c). A more radical proposal is that the extremely high magnitude of the 1755 event is better explained by the near simultaneous occurrence of two earthquakes, one located on the Lower Tagus Valley fault (Figure 4c), which then triggered a larger event on the Gorringe Bank (Vilanova *et al*. 2003), while a study by Gutscher (2004) suggests that a major slip on a postulated major subduction zone in the Gulf of Cadiz was responsible. Gutscher (2004) argues that only a failure plane of at least 200 km in length would be capable of producing such a high-magnitude earthquake and tsunami and all other tectonic structures in the region are too small (see also Gutscher *et al*. 2006; Zitellini *et al*. 2009). The debate shows no evidence of diminishing and has recently come full circle. Barkan *et al*. (2009) have modelled tsunami impacts both close to the epicentre (i.e. near-field effects) and at distance along the east coast of the USA (i.e. far-field effects), and have made the case once more for an epicentral location just to the south of the *Gorringe Bank*.

Depending upon whether 1732 or 1756 population figures are used (Silva-Lopes 1841), the 1755 disaster killed between 1.3% and 1.6% of the people of the Algarve, which compares with the estimated 3.3% who perished in Lisbon, a figure that reflects the effects of fire and overcrowding (Pereira de Sousa 1915, 54; Costa *et al*. 2005, 44). The overall pattern of earthquake losses shows almost complete devastation closest to the most commonly suggested epicentre to

Table 1 The impact of the 1722 earthquake and tsunami. Earthquake losses are related to the EMS-98 scale (Grünthal 1998)

EMS-98 intensity	Definition[1]	Description[1]	Effects of the earthquake and tsunami on the principal town or city of the *concelho* and other important settlements
Greater than IX	Destructive	Intensity IX General panic. Many weak buildings collapse. Even well-constructed buildings show very heavy damage: serious failure of walls and partial structural failure	**Tavira** (MSK – intensity *c*. IX+) 27 houses were destroyed and the *Convento de S. Francisco* was badly damaged. Some casualties were recorded. Great panic occurred in the *convent* because supper was being served in the refectory at the time the earthquake struck. Low lying areas were inundated by the tsunami. **Faro** (MSK – intensity *c*. IX) Some casualties, some houses lost their roofs and the cathedral tower was damaged and the bells rang. Coastal areas affected by the tsunami. **Loulé** (MSK – intensity *c*. IX) Destruction of housing together with the convent (i.e. *Convento dos Capuchos*).
Greater than VIII	Highly damaging	Intensity VIII Many people find it difficult to stand. Many houses have large cracks in their walls, while weak older structures collapse	No information on the settlements affected.
Greater than VII	Slightly damaging	Intensity VII Many people are frightened and run outdoors. Some objects fall. Many houses suffer slight non-structural damage such as hair-line cracks and falls of small pieces of plaster	**Albufeira** (MSK – intensity *c*. VII+) Part of the castle wall collapsed and major damage to the fabric of the settlement is noted in the sources. **Lagoa** (MSK – intensity *c*.VII+) Major damage to housing, to the church and to the *Mosteiro do Carmo* (i.e. Carmalite monastery). **Castro Marim** (MSK – intensity *c*.VII) Major damage to the castle and warehouses. **Portimão** (then known as Vila Nova de Portimão) (MSK – intensity *c*.VII) Strongly felt and severely damaged the *Igeja e Convento dos Capuchos* (Church and Convent of the Capuchin Friars) and the *Igreja do Colégio da Companhia* (Church of the College of the Companions of the Jesuits).

[1]Definitions are from Grünthal (1998, 99)
Source: Based on information from: Moreira de Mendonça (1758, 92–3). Additional data from: Pereira de Sousa (1915); Chagas (2004); Costa *et al*. (2005); Almeida *et al*. (2006) and Baptista *et al*. (2007). It should be noted that there are small differences in intensity estimates between Almeida *et al*. (2006) and Baptista *et al*. (2007) and the figures quoted in the table refer to the latter source. Tsunami effects were felt from Faro to Tavira (Borges *et al*. 2001)

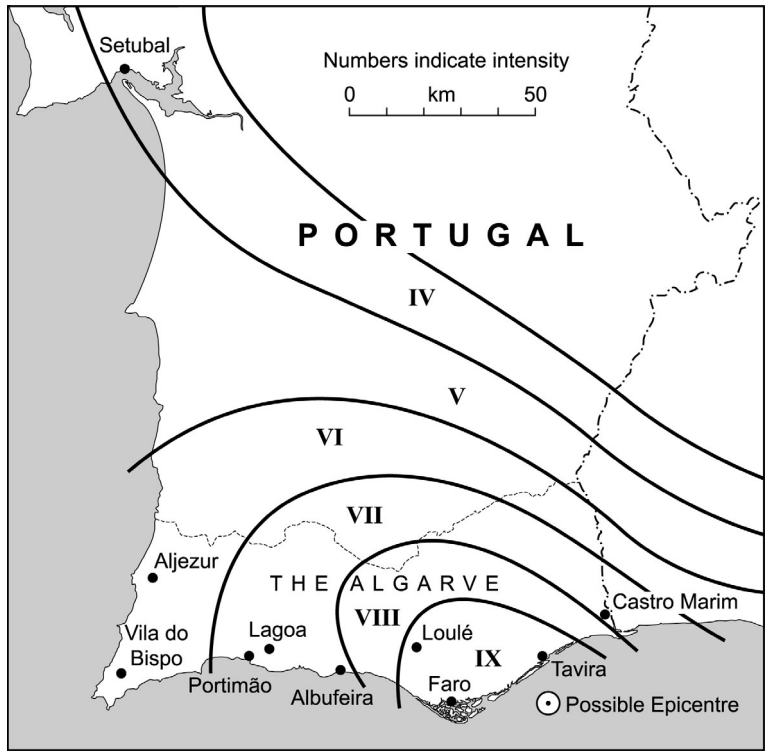

Figure 3 Map showing the intensity of the 1722 earthquake. The map is based on Baptista *et al*. (2007, 372, Figure 1) and, although the data in Table 1 may be interpreted in different ways so as to produce some cartographic variation (e.g. compare Oliveira 1986 with Baptista *et al*. 2007), these are small differences and do not affect the discussion of the event. Isoseismal lines are plotted using the MSK scale, which is virtually identical to the EMS-98 scale (Anon 2009a)

the southwest of Lagos (Figure 4a) and rapid attenuation to the north and east, with mortality rates of *c*. 4% in Lagos, *c*. 1% in Portimão and Faro, less than 1% in Monchique, Tavira and Castro Marim, and no deaths in Alcoutim (Figures 1 and 4a)[8].

Three additional points may be made about the nature of earthquake losses. The first concerns what has been termed *three-way harmonic interaction* and involves the resonance coupling of earthquake waves, surficial deposits and buildings (Degg 1995). First researched intensively following the Mexico City earthquake of 1985 where damage was enhanced on lake-bed deposits (Degg 1992), in Iberia generally (Degg and Doornkamp 1994, ch. 2.5.30) and particularly in the Algarve this is also highly relevant because of the wide diversity of rock types and associated soils that are found and which have varying seismic properties. In the last 10 years research has been carried out in the Algarve on future seismic hazards and this has included the classification of soils and sediments into a number of categories based on their seismic properties, particularly their average shear wave velocity (V_s) (Anon 2004; Oliveira *et al*. 2004; Oliveira 2006; Teves-Costa and Almeida 2006; Carvalho *et al*. 2008a 2009; Roca *et al*. 2008). The lower the V_s value the higher the seismic enhancement, and in all classifications low V_s values have been estimated for some of the soils developed on the *Faro-Quarteira* sand or *Ludo Formation* (Figure 2), and more generally on alluvial deposits, muds and sands. Recently San-Payo *et al*. (2009) have correlated damage in Lisbon with geological outcrops and related soils and have found that the largest proportion of building collapses occurred on alluvium and other surficial deposits and the least on solid rock. In the Algarve one of us has argued (Chester 2001, 376; 2008, 83) that in 1755 there may also have been a strong spatial correlation between building damage and outcrops of soils and sediments with low V_s values. In Tavira, for example (Table 2 and Figure 4a), urban areas near to the coast and river which were built on alluvium and other unconsolidated sediments were more seriously affected than those positioned inland and erected on limestone. In contrast, Faro, which is only 29 km from Tavira, is almost wholly built on

Table 2 1755: earthquake losses for the principal settlements in the Algarve, related to the EMS-98 intensity scale (Grünthal 1998)

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] Settlements are listed at increasing distance from an assumed epicentre on the Gorringe Bank
Greater than XI			**Sagres** All houses were destroyed, together with the Baleeira and Zavial forts. With the exception of the walls of the Sagres fortress, all other substantial state, religious and private buildings were either severely or badly damaged. 2 km north north-east of Cabo de São Vicente (Figure 4a) at the Praia do Talheiro a major – 0.85 km – landslide occurred.
			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 were unaffected, but other chapels were 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. It is estimated that 9 out of 10 houses were rendered uninhabitable. In the adjacent village of Bensafrim all the houses and the parish church were destroyed.
			Aljezur The castle, the parish church and many houses were totally destroyed. Virtually all remaining houses were severely damaged.
			Alvor (sometimes known as Albor at the time – Landmann 1818) 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. The town walls were also severely 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. Only 20 houses remained standing. Some people were killed at mass in the cathedral.
			Albufeira The parish church and many houses were totally destroyed. Some of the houses around the church of Santa Ana disappeared without trace. An important bridge was destroyed.
			Boliqueime All the houses and the church were reduced to rubble.

Table 2 Continued

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] Settlements are listed at increasing distance from an assumed epicentre on the Gorringe Bank
X	Very destructive	Many ordinary well built buildings collapse	
IX–X			**Monchique** The convent was totally destroyed, most other religious buildings were severely damaged. The majority of houses suffered only minimal damage.
			Olhão The church tower was totally destroyed, the *Templos* (temple) and most houses were damaged. Overall Olhão was one of the least badly affected settlements
			São Brãs de Alportel Parish church damaged. Details of the impact on São Brãs are sparse.
			Tavira The church hospital, some religious buildings and houses were destroyed. Other religious buildings were severely damaged. Damage was concentrated near to the river and coast. Not so badly damaged as Lagos and Faro, the other major settlements of the Algarve and many houses survived. Most of the buildings were repairable.
IX	Destructive	General panic. Many weak buildings collapse. Even well constructed 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. Major damage within the Medieval walls, some damage to the warehousing, but many buildings survived.
			Alcoutim Little damage is recorded.
VIII	Highly damaging	Many people find it difficult to stand. Many houses have large cracks in their walls. A few well built 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 4 is based on the more comprehensive definitions (see Grünthal 1998, 99)

[2]Based on: Moreira de Mendonça (1758); Landmann (1818); Silva Lopes (1841); Pereira da Sousa (1915); Pereira de Sousa (1932) and Costa *et al*. (2005). Additional information from: Oliveira (1905 1906); Stanislawski (1963); Botão (1992); Frazão M De Mendóça (1992); Mabberley and Placito (1993); Brooks (1994); Amado (1995); Lameira (1996); Louro (1996); Santos (2001); Garcia-Domingues (2002); Marques (2001 2005 2007); Paula (2001 2006); Santos (2001); Serrão (2001); Chagas (2004); Fonseça (2005); Almeida *et al*. (2006); Carvalho and Vidigal (2006); Anon (2008a 2008b); Paice (2008); Garcia and Cunha (undated)

Source: The table is based on Chester (2008, 81, Table 1), the sources cited and Pedegache (1756). For information on minor settlements reference should be made to Costa *et al*. (2005, 91–92, Table 3 and 113, Table 4)

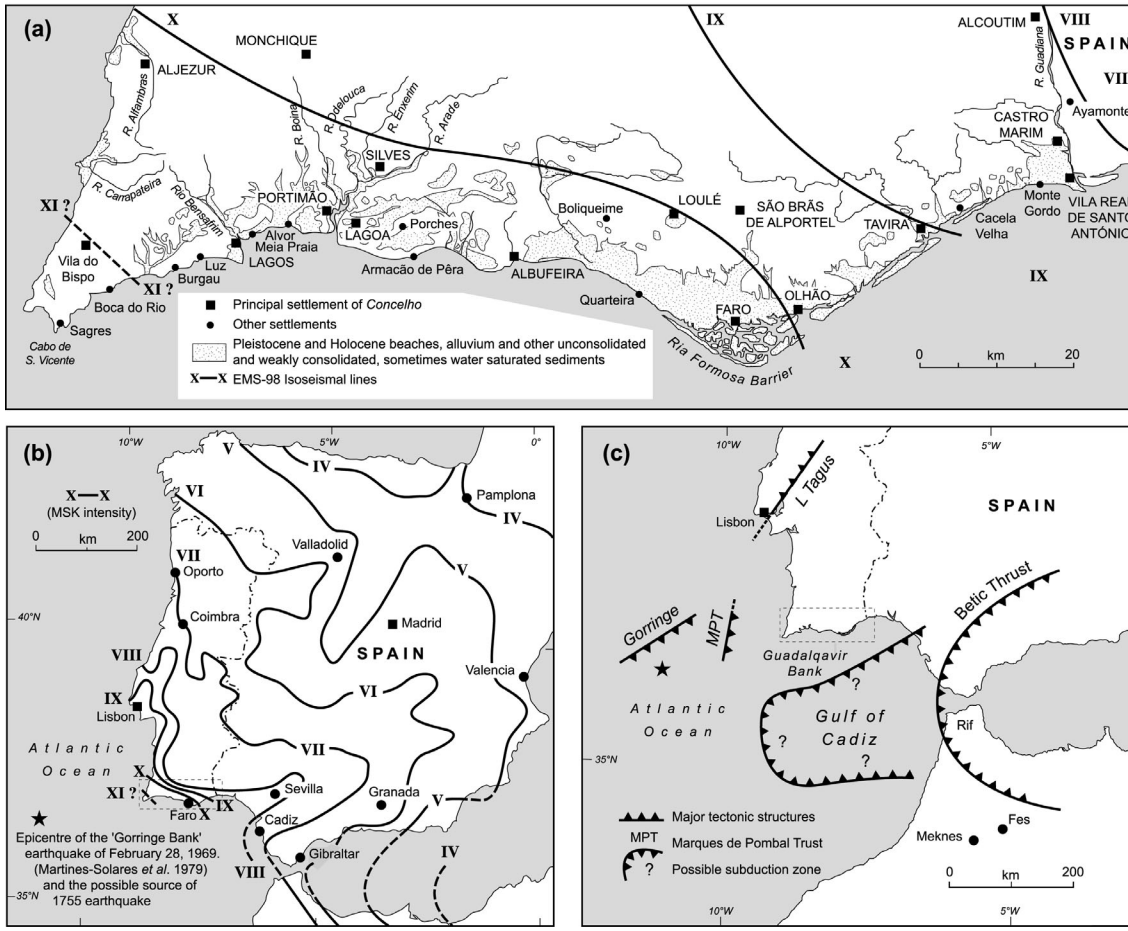

Figure 4 Features of the 1755 Lisbon earthquake. (a) Zones of differing intensity (EMS-98) in the Algarve (modified from Chester 2008, 82, Figure 2). For most historical earthquakes data do not allow the differentiation of intensities of X and XI (Grünthal 1998), but using the data in Table 2 a case may be made for plotting an intensity XI isoseismal line to the west of Lagos. (b) Isoseismals showing the effects of the earthquake on Iberia and adjacent areas of North Africa (based on Martínez-Solares *et al*. 1979; Elmrabet *et al*. 1991; Levret 1991; Degg and Doornkamp 1994, ch. 2.5.12; Chester 2001; Martínez-Solares and López-Arroyo 2004). (c) The tectonic structure of southern Iberia, North Africa and the Western Mediterranean regions (Gutscher *et al*. 2006, 154, Figure 1)

Pleistocene and Holocene formations and was much more severely affected. In 1755 liquefaction[9] was noted in fine grained weakly consolidated sediments along the Spanish to the east of Ayamonte (Figure 4a) (Martínez-Solares and López-Arroyo 2004) and, although this is not mentioned in the historical record, it is almost certain that this must also have occurred in the Algarve and is a significant future hazard (see below).

A second area of discussion concerns the calculation of seismic intensities and the drawing of isoseismal lines (Figure 4a). For some settlements disaster reports are comprehensive whereas for others they are sparse, and the devastation caused to more substantial buildings owned by private individuals, the state and the church is often over-represented in archival sources in comparison with that wreaked on more modest dwellings (Martínez-Solares and López-Arroyo 2004). In the case of the *Parochial survey* this is exacerbated because questionnaires were completed by parish priests who usually provided information on ecclesiastical losses in some detail, but varied in their diligence in recording other information (Costa *et al*. 2005, 219–37).

Figure 5 A typical *Type II* building in Portimão. This is the *Igreja do Colégio dos Jesuitas* mentioned earlier in the paper. It was extensively damaged in both 1722 and 1755 *Source*: Photograph by David Chester

A third point about earthquake losses involves the effects on different types of building. In their comprehensive study of the effects of the 1755 disaster in southern Spain, Martínez-Solares *et al*. (1979) and Martínez-Solares and López-Arroyo (2004), recognise two categories of construction both of which were also to be found in the Algarve (Murphy-Corella 2009):

1 *Type I (high-frequency structures)*: small masonry one- and two-storey buildings made from stone, ashlar blocks, brick and rubble; and
2 *Type II (low-frequency structures)*: architecturally more complex and taller; churches, public buildings, castles and monasteries (Figure 5).

Present day studies of the vulnerability of settlements in the Algarve and simulations of the ways buildings might perform in future earthquakes show the dangers inherent in stone and brick construction (Oliveira *et al*. 2004; Rio and Almeida 2006; Rio *et al*. 2006), and these findings go some way to explain the pattern of losses. Near to the epicentre devastation was virtually total and affected both Type 1 and Type II buildings both of which were constructed using traditional materials (Table 2), however at increasing distances the pattern changed with the proportion of Type II structures being damaged rising as a percentage of total losses. Hence in Ayamonte just over the Spanish border (Figure 4a), which is located more than 300 km from the *Gorringe Bank*, taller buildings experienced far more damage than low rise ones (Degg and Doornkamp (1994), a pattern that was repeated across southern Spain (Martínez-Solares and López-Arroyo 2004; Martínez-Solares *et al*. 1979; see also Udias and Arroyo 2009). A similar pattern of losses was also evident in the Algarve (Table 2) and the rest of Portugal, as seismic wave attenuation occurred towards the north and east (Oliveira 1986). In Tavira, for example, many Type II ecclesiastical and public buildings were destroyed, but people living in Type I housing suffered fewer losses than in towns located closer to the epicentre (Stanislawski 1963, 132–3; Serrão 2001).

The reasons for this distribution are two-fold. First, high-frequency earthquake waves are more rapidly attenuated than low-frequency waves so that in Lisbon, Spain and the eastern Algarve there was more damage to Type II buildings. Second, damage is inversely corrected with building rigidity. Low-rise housing is more rigid than the more structurally complex public and ecclesiastical structures, and at distance from the epicentre the latter are disproportionately affected (Oliveira 1986; Mendes-Victor 1987; Tiedemann 1991; 1992, 350–1).

The impact of the 1755 tsunami

In assessing damage caused by the tsunami (Table 3) similar sources to those used in evaluating the impact of the earthquake (Table 2) may be employed, to which historical cartography (Mader 2001; Andrade 1992; Andrade *et al*. 2004; Costa *et al*. 2005) and the evidence provided by the sedimentary record may be added (Dawson *et al*. 1995; Hindson and Andrade 1999; Hindson *et al*. 1999; Luque *et al*. 2001; Allen 2003; Dawson and Stewart 2007; Morales *et al*. 2008). In view of the damage caused by the tsunami (Table 3), the death toll of *c*. 440 (Costa *et al*. 2005, 44) is not as high as might be expected. The fact that no deaths were recorded in any of the settlements to the west of Lagos, the zone closest to the epicentre, may reflect the high cliff lines that dominate much of this area and which provide protection, low population densities and/or a lack of veracity in this portion of the historical data. The latter possibility seems unlikely, however, because, apart from the bias already noted in favour of recording ecclesiastical losses, sources are generally accepted as reliable (Costa *et al*. 2005).

In the Algarve there are a number of sites where tsumami sediments have been studied including: the Boca do Rio west of Lagos; the Alvor estuary; the Rio Arade near to Portimão; the Rio Formosa Barrier Islands near to Faro and the Spanish coast to the east of the Rio Guadiana. At Boca do Rio (Figure 4a), a sediment core reveals that sediment representing *c*. 700–800 years of deposition was eroded by the tsunami (Allen 2003, 269), while other researchers (e.g. Dawson *et al*. 1995; Hindson and Andrade 1999;

Table 3 1755: summary of the principal attributes and impacts of the tsunami in the Algarve

	Details
Attributes	Following the earthquake, the tsunami took 16 min to travel to Cabo do S. Vicente and 30 min to reach the Spanish border. Lisbon was affected 30 min after the earthquake, the Gulf of Cadiz after 30–78 min (estimates vary), Madeira after 90 min and Martinique after *c*. 600 min. The seabed was exposed in many areas before the tsunami struck. Run up heights varied from 11 to 30 m according to some sources, although the latter figure may be exaggerated.
Area affected	
Cabo do S. Vicente to Lagos	**Arrifana fortress** (north of C. S Vincente) was destroyed by waves, but may have been partially damaged by the earthquake.
	Sagres Destroyed by what some sources claim was a wave *c*. 30 m height, although this may be an exaggeration. Beach pebbles and fish were deposited in the town. At Martinhal beach there was a marine incursion of *c*. 2 km and blocks weighing *c*. 4500 kg were deposited.
	Lagos The walls of the town, a church, two fortresses and many houses were virtually destroyed. Enormous quantities of debris from the tsunami (and earthquake) raised the level of the city by up to 1 m. 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 600 m inland and destroyed buildings on land up to 30 m in height. The chapel of *Nossa Senhora da Ajuda,* located on the beach, was totally destroyed.
	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 880 m inland, and spread 5 km up the Rio Arade. Some 13% of the present-day *concelho* was flooded.
	Waves at the coast may have been *c*.20 m at Alvor and somewhat lower at Portimão.
Portimão to Albufeira	In Albufeira and Quarteira there were many changes in 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. Fish were deposited on the beach.
Albufeira to Faro	**Quarteira** Some fisherman's cabins were destroyed.
	Faro The city was largely protected by the Rio Formosa Barrier System (Figure 4a), but historical cartography 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.
General effects on the coastal zone and small settlements	Many changes in the relative elevation of land and sea and noted in the literature, and several small rivers were choked with sediment near to their mouths. The effects of the tsunami on soil salinity and, hence, fertility was not recorded in the historical record but may have been locally significant.[1]

[1]Based on information in: Silva Lopes (1841); Pereira de Sousa (1932); Stanislawski (1963); Carrapico *et al*. (1974); Elmrabet *et al*. (1991); Andrade (1992); Mader (2001); Andrade *et al*.(2004); Brooks (1994); Costa *et al*. (2005); Fonseça (2005); Kozak *et al*. (2005); Almeida *et al*. (2006); Paula (2006); Kortekaas and Dawson (2007); Mhammdi *et al*. (2008); Paice (2008); Tedim-Pedrosa and Conçalves (2008); Baptista and Miranda (2009)

Source: The table is amended from Chester (2008, 84, Table 2) and is based on the sources cited above

Hindson *et al*. 1999) have concluded, *inter alia*, that the 1755 event:

1 was associated with both erosion and deposition;
2 did not move significant volumes of sediment from the offshore zone, but rather involved material from beaches and dunes with shell fragments, marine macrofossils, soils, estuarine silts and clay being deposited;
3 caused the rapid sedimentation of a chaotic assortment of materials of differing grain size; and
4 had run-up wave heights which were higher than the upper altitudinal limits of sedimentation.

The latter point has major implications for future planning because the limit of sedimentation determined in the field cannot be used to define the area which would inundated under future hazard scenarios. Recourse must be made to the historical record.

As Table 3 shows, in places the tsunami penetrated a considerable distance inland and figures of 2.5 km are quoted for Lagos and Armação, and 660 m for Alvor (Tedim-Pedrosa and Conçalves 2008, 60). Tsunami waves must also have flowed up the valley of the Rio Guadiana (Figure 4a) because both Castro Marim and Ayamonte were severely affected. As one of us has noted elsewhere (Chester 2008, 85), the stagnant, malarial character of the Rio Arade at Silves in the late eighteenth and early nineteenth century (Chester and James 1991) may be due in part to the deposition of sediment brought up the river from the coast, and Tedim-Pedrosa and Conçalves (2008, 61) argue that waves advanced up the river some 5 km, although human-induced erosion within the catchment of the Arade may have been a more potent factor controlling this phase of sedimentation (Chester and James 1999).

Estimates vary, but the time taken for the tsunami to reach different sections of the Algarve coast range from around 16 to 30 min (Tedim-Pedrosa and Conçalves 2008). Run-up heights were generally, but not always, greatest in the west (i.e. nearest to the epicentre) and showed an irregular decrease with distance, due to geomorphological factors and the state of the tide (Andrade 1992; Mendes *et al*. 1999, 141), of which the most important influences were the shape of coast and the bathymetry of the offshore zone. The tsunami struck the Algarve at low tide and run-up heights varied over a short distance; for example, in the Bay of Cadiz from 11 to 20 m (Martínez-Solares *et al*. 1979). There are difficulties in interpreting the historical record to produce estimates of run-up heights and different writers produce conflicting figures. For example, Kozák *et al*. (2005, 38) argue a case for wave heights of 30 m at Sagres and Alvor, 12 m at Quarteira and 4 m at Portimão. In contrast, Tedim-Pedrosa and Conçalves (2008, 61) propose typical heights of 10–15 m for the southwest Algarve and at least 20 m for Alvor, with the chapel *Nossa Senhora da Ajuda* located on the beach being totally destroyed.

Recovery

In contrast to volcanic eruptions and major floods and with the exception of the spatially limited areas adversely affected by tsunami deposits, earthquakes do not normally sterilise agricultural land. This, combined with the resilience of subsistence agriculture, meant that both cropping and grazing could recommence almost immediately. Food supply was assisted by the fact that 1755 was a year of rich harvests throughout Portugal (Francis 1985, 123) and there was no evidence of starvation, with prices of wheat remaining stable in Faro during 1755/6. In 1756/7 and in spite of price controls (see below) wheat prices rose by 66%, although this figure is much lower than that recorded in Lisbon, and prices began to decline by 1757/8 (Pereira 2009, 478). Most farmers lived in Type I buildings, and away from the western Algarve where damage was almost total affecting buildings regardless of construction, most dwellings of this type survived.

In the eighteenth century migration to other regions of Portugal and abroad was an established part of Algarvian demography, with farmers and fishermen supplementing their incomes. Although there is some evidence that numbers were swelled and that visits increased in length, for example in 1753 only 2% of Gibraltar's population was Portuguese whereas this rose to 20% in 1814 (Borges 2000), it is not possible to ascribe these changes solely or even principally to the effects of the earthquake. Although there are differences between sources, there is no evidence of population decline within the Algarve. Small decreases in the immediate aftermath of the earthquake occurred in Monchique, Lagos and in some of the smaller settlements in the far west, but the overall picture is one of stability between 1756 and 1758 (Santos 2001) and, thereafter, a significant rise from 81 417 in 1756 to over 105 000 in 1802 (Silva-Lopes 1841). Foreign travellers in the late eighteenth and early nineteenth centuries have left accounts which indicate a generally vibrant agricultural economy and a people who, although poor, were well fed. Acute poverty was confined to the area west of Lagos (Figure 4a) (Link 1801; Landmann 1818).

Responses to disasters in pre-industrial societies are characterised by elements of both resilience and vulnerability (Chester *et al*. 2005; Gaillard 2007). Whereas subsistence agriculture is characterised by its resilience, urban-based activities, especially com-

merce and trade, are notable for their vulnerability. Writing from Faro, an English correspondent of the *Gentleman's Magazine* describes the population as initially 'living in the fields' (Anon 1755, 563), probably because some people had lost their homes and other were worried about aftershocks. As Tables 2 and 3 show, earthquake damage to the urban fabric and the effects of the tsunami on the coast, ports and formerly navigable rivers were substantial.

The Marquês de Pombal's first action following the earthquake was to send troops to the Algarve in order to forestall north African corsairs from exploiting the situation and to maintain law and order (Dynes 2005, 41), but more substantial measures soon followed (Jorge *et al*. 2005). These policies were the first example anywhere in the world of the State assuming responsibility for planning a co-ordinated centralised response following an earthquake (Fonseça 2005). Pombal viewed the Algarve as a region with considerable economic potential (Correia 1997) and initiated a comprehensive recovery programme entitled *Restauração do Reino do Algarve* (*Restoration of the Kingdom of the Algarve*). This programme and other legislative initiatives enacted in the 1760s and 1770s included, *inter alia*: temporary price controls; taxes on imports; the establishment of artisan-based industries, such as a tapestry works in Tavira (Conceição 1829; Serrão 2001 2007; Betâmio de Almeida 2009); agricultural marketing reforms; and the removal of the remaining legal penalties against *new Christians* and racial minorities, because both groups were economically important within the commercial sector (Saraiva 1997, 78; Correia 1997). Pombal's major achievement, however, was the planning of a new town, based on the existing small village of Vila Real de Santo António which faced the Spanish border (Figure 4a). From the 1750s relations between Spain and Portugal were strained because of conflicts over fishing rights in the Algarve and border disputes in South America, and the new town was planned for strategic as well as economic reasons, the aim being 'to show a strong centralised state that followed the path to modernity' (Jorge *et al*. 2005, 81). Designed by Reinaldo Manuel dos Santos of the Lisbon public works planning office (the *Casa do Risco*), which was set up by Pombal to reconstruct Lisbon (Anon 2008a; Jorge *et al*. 2005, 175), Vila Real was built in just few months in 1773–4, being laid out using a grid iron pattern around a central square (Figure 6). Major buildings were constructed in Lisbon as pre-fabricated units and brought to the Algarve by ship and many of the earthquake-proofing procedures used in Lisbon were also employed in Vila Real, including the use of a pioneering anti-seismic woodem framework, or *gaiola* (cage) which was built into the outer walls of the town's principal buildings (Tobriner 1980; Silveira *et al*. 2007).

Figure 6 The 'Pombaline' architecture of the new town of Vila Real de Santo António
Source: Photograph by David Chester

Although the initiatives taken by Pombal were important, recovery of the non-subsistence economy and the urban fabric took many decades. It was only in 1798, for example, that the eastern bridge linking Lagos to the rest of the Algarve was rebuilt, when the traveller H.F. Link (1801) visited at the beginning of the nineteenth century he found Vila Real under populated and substantial areas of Lagos were still in ruins during the 1820s (Paula 2006, 14). It was only with major investment in the region by both Portuguese and foreign financiers and entrepreneurs from the mid-nineteenth century that non-subsistence activities again became important. Fish-canning factories – particularly of tuna and sardines for export – were established in many coastal towns and cities and the cultivation, processing and export of cork oak became important in Faro, Loulé, Portimão, São Bras and Silves (Alves *et al*. undated; Duarte 2003; Feio 1949; Garcia-Domingues 2002; Paula 1992 2006; Anon 2008a – see Figure 1). Even with this stimulus full recovery of the region took time and Faro still showed significant earthquake 'scars' within its urban fabric in the first decades of the twentieth century (Pereira 2006, 25).

Conclusion

In the immediate aftermath of the 1755 earthquake and as the rebuilding of Lisbon was being planned, Pombal's principal architect General Manuel da Maia introduced what is often claimed to be the first earthquake code enacted anywhere in the world. This code included not only the wooden *gaiola*, but also restrictions on building height and unnecessary ornamentation, while streets had to be of minimum width, with

fire breaks inserted between adjacent buildings. Later these lessons were applied to Vila Real de Santo António (Figure 6) and to a lesser extent other towns and cities in the Algarve. When major urban growth resumed in the second half of the nineteenth century, many of the lessons of 1722 and 1755 had been forgotten (Azevedo *et al*. 2009). In Lagos several buildings dating from the late nineteenth century onwards were constructed in complex neo-classical and Art Nouveau styles and were highly decorated with tiles and other ornamentation. In some buildings timber reinforcements were removed in order to open larger shop frontages at ground level and many interior walls were eliminated to produce more substantial rooms (Paula 2006).

Despite a history of damaging earthquakes in the Algarve since 1755 and the repeated poor performance of traditional rubble-stone Type I and Type II buildings, plus certain classes of more modern construction, until the late 1950s little was done to improve the situation. In 1955 a symposium was held to mark the 200th anniversary of the Lisbon earthquake and strongly supported the introduction of a new building code (Ordem dos Engenheiros 1955). This was enacted in 1958, but was generally agreed to have been ineffective (Azevedo *et al*. 2009, 561–2), with more successful policy having to await the introduction of the current code in 1983 (RSA 1983). Even this code has not been without its critics (Azevedo *et al*. 2009, 562) and there is some anecdotal evidence that during the height of the tourist-related building boom of the late 1980s and 1990s the code is not properly enforced in the Algarve (Chester 2001).

The hazard analyst David Alexander (1997) has used the term 'residual unameliorated vulnerability' to describe elements of the heritage of an area which increases its present day exposure to hazard. There is little doubt that buildings constructed before 1958 and in some cases 1983 are particularly vulnerable, but the demographic impact of tourist development which occurred in the Algarve over the past 40 years is also highly significant. At the end of 2008 the resident population of the Algarve was estimated at over 430 000 (INE 2009), this number often doubling at the height of the tourist season in mid-summer. These factors of vulnerability and demography, together with stimulus provided by the 2004 Indian Ocean earthquake and tsunami, have produced an intellectual and political climate in which many studies of hazard exposure have been undertaken both for the Algarve as a whole (e.g. Anon 2004; Tedim-Pedrosa and Conçalves 2008), and for individual *concelhos* (e.g. Oliveira *et al*. 2004; Mendes-Victor 2006).

A contentious issue involves the calculation of recurrence intervals for earthquakes of differing magnitude. For instance, because of debates over the location of the epicentre and faulting mechanisms, the recurrence interval of a '1755 type scenario' varies between authors depending upon the assumptions that are made in the calculation. For many years Portuguese geophysics and hazard planners assumed an epicentre on or near to the Gorringe Bank and this produces a recurrence interval of 614 ± 105 years (Mendes-Victor *et al*. 1994, 269), whereas by using an alternative epicentral location Tedim-Pedrosa and Conçalves (2008, 62) argue for a return period of *c*. 1000 years. For Rio *et al*. (2006) the probability is even lower, with only a 12% chance in 200 years of an event exceeding a magnitude of 8 M_w occurring in the ocean to the southwest of the Algarve, which equates to a return period of 1479 years.

Studies of individual *concelhos* have focused on Faro (Anon 2004) and Lagos (Mendes-Victor 2006). Research has used earth and social science-based perspectives to integrate: investigations of the vulnerability of buildings of different types, demography and social impacts; with parallel studies of likely earthquake scenarios, their recurrence and possible interactions between earthquakes, soils and bedrock, and areas that would be flooded and/or affected by liquefaction. Another study has been carried out in Portimão *concelho* (Tedim-Pedrosa and Conçalves 2008) and has investigated the area of the city that would be affected by a 1755-type tsunami. Using 1: 5000 scale maps and detailed study of the 1755 inundation, the authors concluded that today some 24 km^2 of territory would be affected , which would represent *c*. 13% of the total area of the *concelho* and affect *c*.18 000 residents and *c*.40% of the tourist hotels.

Although these studies are impressive there is a widely recognised need for similar studies to be carried out in all the *concelhos* of the Algarve. In February 2008 the Minister of the Interior gave a progress report on a programme initiated in 2007 entitled *Estudo do Risco Sísmico e de Tsunamis para o Algarve* (*Study of Seismic Risk and Tsunamis in the Algarve*) (Anon 2009b). With a budget of €2 million, this involved the production of a hazard plan for each *concelho* and initial results were made available by the end of 2008. Testing and review are taking place at the time of writing and publication will follow once the plan has been approved by the Portuguese government. It is sobering to reflect that without any intervention, losses would be severe. Statements by the Minster of the Interior in 2008 suggest up to 3000 people would die and 27 000 people would be made homeless should a magnitude 8.5 M_w 1755-type scenario recur.

What is more worrying is that, despite being a smaller event, because it would affect the more densely populated central Algarve, which is more frequently visited by tourists, a 1722-type 'Tavira' scenario would cause far higher casualties and much more damage, estimates being c. 12 000 deaths with

some 18 000 buildings being destroyed (Anon 2008c 2008d). Rio *et al*. (2006) divided the Algarve into three seismic zones. In the most easterly zone, which includes Tavira, return periods were calculated for earthquakes of differing magnitudes. Estimates of the magnitude of the 1722 earthquake vary from 6.5 M_W (Baptista *et al*. 2007) through 7.0 M_W (Oliveira 1986) to 7.8 M_W according to Almeida *et al*. (2006). If the latter is correct than the return period exceeds 3000 years and may be as high as 7000 years or even higher. If the high rates of damage in 1722 were caused by a magnitude 6.5 M_W earthquake, then an event of similar size might be expected once every 595 years and the region would be extremely vulnerable to earthquakes and tsunamis of this type. Indeed the probability of an earthquake exceeded magnitude 6 M_W in the eastern Algarve is estimated at 32% in 100 years and 54% in 200 years (Rio *et al*. 2006). More robust magnitude estimates for 1722-type events are clearly required to resolve this aspect of disaster planning.

In another recent study, Nunes *et al*. (2009) have constructed a digital terrain model (DTM) of the Algarve. Using historical data on tsunamis they have assessed those areas at risk using three scenarios which involve enhanced wave elevations of 3, 5 and 7 m. The principal findings are that:

1 apart from the Boca do Rio (Figure 4a), the area west of Lagos would be little affected by tsumani waves of these heights;
2 from Lagos to Portimão, 14% and 44% of the urban area would be exposed, respectively, to the 3 and 7 m scenarios; and
3 from Faro to Vila Real de Santo António the impact would be the most severe. A 3 m scenario would cause 17% of the urban area to be affected, this figure rising to 60% and 77%, respectively, for the 5 and 7 m scenarios. This highlights again how vulnerable the Algarve is, not only to 1755-type events, but also to earthquakes and tsunamis of similar magnitude and location as those which occurred in 1722.

Acknowledgements

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Notes

1 Magnitude is a quantitative measure of earthquake size. For many years a scale devised by Charles Richter in California in 1931 was widely used and is still frequently (and often erroneously) quoted in popular accounts. Known as the Richter (or local) magnitude (M_L), for each unit increase in magnitude, the amplitude of seismic waves increases 10 times and the energy released over 30 times (e.g. a magnitude 8.6 earthquake releases *c*.1×10^6 the energy of a magnitude 4.3 event). Other magnitude scales are: the surface wave magnitude (M_S); body-wave magnitude (m_b) and the moment magnitude (M_W). The M_W scale is the one most frequently quoted in official accounts because it most accurately allows the comparison of earthquakes of differing size (Bolt 2004, 163–70).

2 Major earthquakes occurred in: 63 BCE (southwest of Cape St Vincent – estimated magnitude 8.5); 47 BCE (estimated magnitude 8.5); 33 BCE (estimated magnitude 9.0?); 309 CE (west of Cape St Vincent – estimated magnitude 7.0); 382 (southwest of Cape St Vincent – estimated magnitude 7.5); 1309 (west of Cape St Vincent – estimated magnitude 7.0); 1353 (Silves – estimated magnitude 6.0); 1356 (southwest of Cape St Vincent – estimated magnitude 7.5); 1504 (in the vicinity of Carmona, Seville, Spain – estimated magnitude 7.0); 1531 (Lower Tagus region, near Lisbon – estimated magnitude 7.1); 1587 (in the vicinity of Loulé – estimated magnitude 6.0); 1719 (in the vicinity of Portimão – estimated magnitude 7.0); 1722 (in the vicinity of Tavira – estimates of magnitude vary from 6.5 (Baptista *et al*. 2007), through 7.0 (Oliveira 1986) to 7.8 (Almeida *et al*. 2006); 1755 (southwest of Cape St Vincent or elsewhere – estimated magnitude 8.5); 1856 (northeast Algarve/southwest Alentejo – estimated magnitude 6.0); 1858 (Lower Tagus region, near Lisbon – estimated magnitude 7.2); 1896 (south Alentejo – estimated magnitude 5.0); 1903 (Lower Tagus region, near Lisbon – estimated magnitude 6.3); 1909 (Lower Tagus Valley, near Lisbon – estimated magnitude 6.3); 1915 (north of Cape St Vincent – estimated magnitude 6.6); 1921 (west of Algarve – estimated magnitude 4.3); and 1969 (southwest of Cape St Vincent – estimated magnitude 7.5).

3 Based on information in Almeida *et al*. (2006); Baptista *et al*. (2007); Choffat and Bensaude (1912); Costa *et al*. (2005); Galbis Rodriguez (1932); Mezcua (1982); Oliveira (1986).

4 Estimating the magnitudes of historical earthquakes is problematic. Some early estimates using Californian 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 (Tiedemann 1991, 23; 1992).

5 The *Marquês de Pombal's survey* has been called 'one of the foundational documents of modern seismology' and comprised a 13-question survey relating to all aspects of ground shaking. These included, *inter alia,* questions on: mortality, building damage, earthquake history, tsunamis, shortage of food and fire damage. The term *Marquês de Pombal's survey* is misleading, since it is probably the work of two of his associates: António Ribeiro Sanches and Luís AntónioVerney (Shrady 2008, 144–6). The questionnaires for the 1758 earthquake were sent out by Father Luís Cardosa, who was working at the time on the *Dictionário Geográfico* (Fonseça 2005, 52).

6 Baptista *et al*. (2007) make the point that, although the possibility that the earthquake and tsunami were caused by a large

landslide cannot be definitely ruled out, the balance of evidence points strongly to a tectonic cause. In particular, no landscape scar of the required size has been found and the pattern of isoseismal lines (Figure 3) points strongly to an offshore tectonic source.

7 Intensity is a descriptive measure of the size of an earthquake, which is based on the impact on people, buildings and the ground surface. Isoseismal lines are used to join places of equal intensity and there are several scales, of which the Modified Mercalli (MM) and the Medvedev-Sponheuer-Kárnik (MSK) scales widely used by European seismologists are the most well known. In 1998 a new scale particularly suitable for use in Europe was published (EMS-98) and is virtually identical to the MSK scale. All intensity scales run from I (minimum) to XII (maximum). Being based on descriptions of recorded damage, intensity may be calculated for both historic and contemporary earthquakes.

8 The highest death toll occurred in the small village of Boliqueime east of Loulé (Figure 4A), where 96 inhabitants (*c.* 6% of the total) were killed when the parish church collapsed. In Albufeira 204 people (*c.* 4% of the total population) perished: 197 due to tsunami inundation and seven as a direct result of the earthquake (Figure 1 – Costa *et al.* 2005, 44).

9 Liquefaction (or liquefaction) occurs in fine-grained saturated soils and unconsolidated deposits. When shaken in an earthquake 'the pressure of water between the grains increases until eventually the sediment takes on the character of a dense liquid rather than that of a solid (Bolt 2004, 249–50).

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