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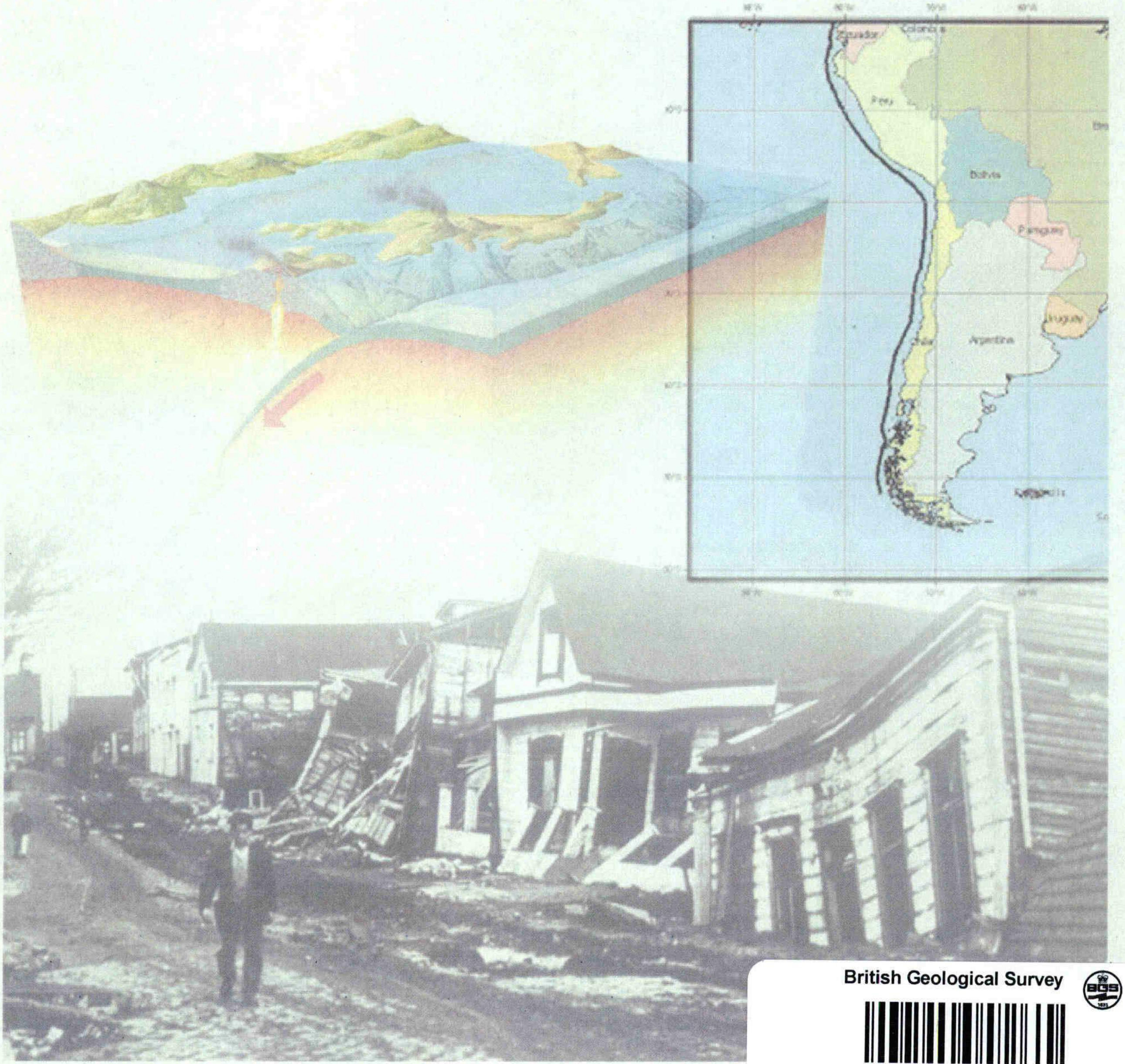
Subduction zones with potential for PSInSAR investigation for space-based disaster reduction

SL Sargeant and RMW Musson

BGS Technical Report CR/04/158N



BRITISH GEOLOGICAL SURVEY

TECHNICAL REPORT CR/04/158N

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Cover image

Damage from the great subduction earthquake of 22 May 1960, at Valdivia, Chile.

Key words

Seismic hazard, subduction, remote sensing, InSAR, PSInSAR, space-based monitoring.

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Foreword

The use of PSInSAR (Permanent Scatterer Interferometric Synthetic Aperture Radar) for the study of tectonic deformation has been studied in the context of earthquake risk reduction in the course of the project PSIGN (Musson and Bommer 2002, Musson et al 2002, 2003, 2004 and PSIGN project reports). The test area used in this study was the Tokai area of Honshu, Japan, as this is an area where a devastating great earthquake is considered to be imminent. The study showed that preseismic deformation associated with this impending earthquake could be detected, and these space-based results are confirmed by other methods, including GPS but more importantly, ground levelling studies.

The PSIGN study area is characterised tectonically by a process known as subduction, where one crustal plate (usually oceanic) is being pushed under an over-riding plate (usually continental), down into the earth's mantle, to be destroyed at depth. Because of the broad, shallow-dipping interface between the two plates in such a situation, fault ruptures can have a large area and therefore produce much bigger earthquakes than is possible in other tectonic regimes (such as California). Earthquake risk in such areas is therefore a matter of great concern.

Previous studies in Japan, e.g. those by Yoshioka et al (1993) and Sagiya (1999) have shown that deformation data of this kind can be used to image the locked part of a subducting plate using a mathematical process referred to as the ABIC method (Akaike's Bayesian Information Criterion). Although the PSIGN data has not yet been used in this way (it could be, and we hope that it will be in a future study), as it provides very dense data coverage it has the potential to give a better resolution of the locked zone than could be achieved with other types of data.

In the case of Japan, it has been possible to use the ABIC method in the past because of the existence of good levelling and GPS data. In other parts of the world where such data do not exist in sufficient degree (or do not exist at all), the availability of PSInSAR as a resource would be particularly valuable.

This report provides a short survey of the major subduction zones of the world where PSInSAR could conceivably be used. It considers in particular the tectonic configuration, past seismicity, and the human vulnerability of these zones. Issues relating to the availability of suitable InSAR data archives are not addressed.

Acknowledgements

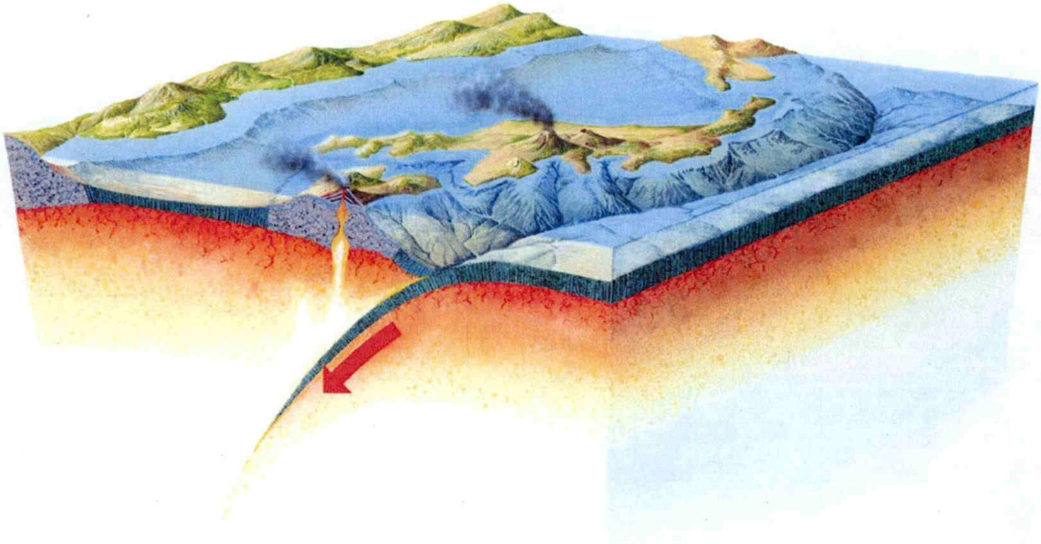
The production of this report was supported by the European Space Agency and the British Geological Survey (NERC).

Table of Contents

1. Introduction

Recent papers by Musson and Bommer (2002), Musson et al (2002, 2003, 2004) have discussed the possible application of the PSInSAR technique to monitoring crustal deformation in subduction zones. These are zones of continental collision where one crustal plate is pushed under another, and is eventually destroyed deep within the Earth's mantle. Such zones are the places where the largest earthquakes in the world occur, and thus, are sensitive from the point of view of earthquake risk.

The picture below illustrates the subduction process (from van Rose and Musson 1997):



In this figure the plate on the right is being pushed under the one on the left. It is called the subducting plate, or subducting slab. The other plate is the over-riding plate. When the subducting plate becomes locked (essentially, it sticks) the over-riding plate is pulled down, and tectonic subsidence is observed. By monitoring this subsidence, one can begin to draw conclusions about where the plate is locked, from which one can further make deductions about the large earthquake that may be waiting to occur. This in turn can be used in the preparation of disaster mitigation planes. Space-based monitoring has the potential to supply this information through the use of PSInSAR. The geodetic data are inverted using a technique known as the ABIC method (Akaike's Bayesian Information Criterion), which is described in detail by Yabuki and Matsu'ura (1992). The method treats the locked part of the subduction interface as if it were undergoing backslip sufficient to cancel out the drive of the plate motion; the extent of this backslip can be solved for from the geodetic data so long as one knows the overall plate velocity.

This report surveys the major subduction zones of the world, discussing each in turn in the context of the tectonics, the seismicity, the exposed population and the earthquake risk. It gives the reader an overview of the potential for the application of space-based monitoring to detect tectonic subsidence with a view to the planning of future projects.

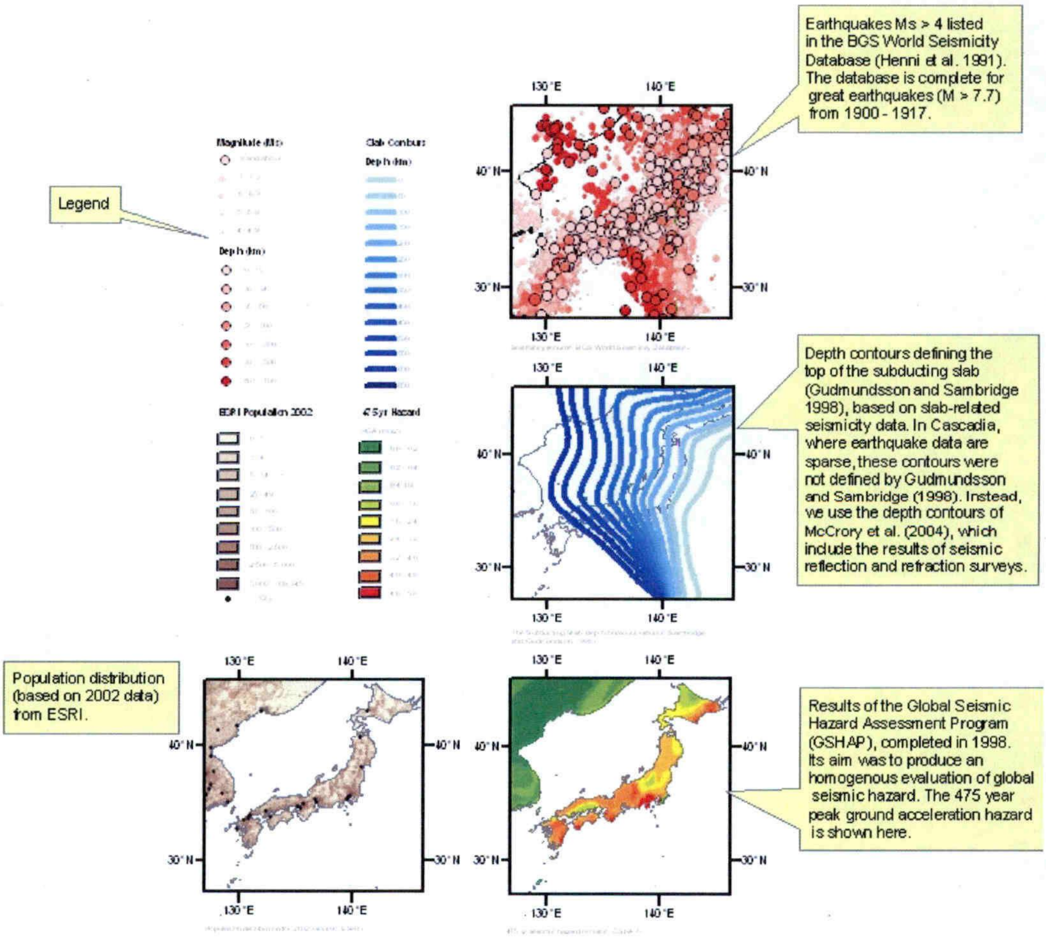
The report is structured as a series of sections on each of the following subduction zones:

- Central America
- Cascadia
- South America
- Japan
- Indonesia
- Alaska
- Aegean
- Northern India

Each section contains the following parts:

Part 1: Summary discussion of the tectonics, seismicity, hazard and vulnerability in the subduction zone region, with remarks on the suitability for PSInSAR. These notes are intended to provide a simple overview of the situation in each zone; it is outwith the scope of this report, for instance, to review in detail the earthquake building codes in each region and their effect on vulnerability, or to try and estimate loss levels in future earthquakes.

Part 2: A series of maps (in the format below), which illustrate seismicity (Ms > 4), depth contours defining the subducting slab, the 475 year peak ground acceleration hazard and the population distribution (as of 2002).



Earthquakes Ms > 4 listed in the BGS World Seismicity Database (Henni et al. 1991). The database is complete for great earthquakes (M > 7.7) from 1900 - 1917.

Depth contours defining the top of the subducting slab (Gudmundsson and Sambridge 1998), based on slab-related seismicity data. In Cascadia, where earthquake data are sparse, these contours were not defined by Gudmundsson and Sambridge (1998). Instead, we use the depth contours of McCrory et al. (2004), which include the results of seismic reflection and refraction surveys.

Population distribution (based on 2002 data) from ESRI.

Results of the Global Seismic Hazard Assessment Program (GSHAP), completed in 1998. Its aim was to produce an homogenous evaluation of global seismic hazard. The 475 year peak ground acceleration hazard is shown here.

Each section begins with a political map of the region with the trench associated with the subduction zone marked.

Some subduction zones are not treated here, either because of a lack of any infrastructure at risk (e.g. Kamschatka - a lack of built environment also inhibits the use of PSInSAR which is largely dependent on urban areas to provide permanent scatterers), a lack of sufficient land area (the Antilles Arc in the Caribbean) or because of other conditions that make it very unlikely that PSInSAR could be used (e.g. the "mini" subduction zone of Vrancea, Romania).

2. Central America

Central America is situated at the point where the Nazca, Cocos, South America and Caribbean plates converge; seismic hazard is high and substandard construction and land management practices leave the many people of this region extremely vulnerable to earthquakes in the subduction zone.

2.1 Tectonic setting and structure of the subduction zone

Central America and Mexico are part of the 'ring of fire' that encircles the Pacific Ocean. Beneath it, the Nazca, Cocos, South America and Caribbean plates converge. Relative to the Caribbean plate, the Cocos plate moves NE at around 120 mm/yr and is subducted beneath the continental crust of Mexico and the Caribbean. The Nazca plate moves in a more easterly direction at a rate of about 54 mm/yr (De Mets et al 1990) and is subducted at the western margins of South America and the Caribbean. The existence of an independent microplate in this system has also been proposed (Westbrook et al 1995).

Regional tectonics are complex and there are regions of subduction, strike-slip faulting and over-thrusting along the western margin of Central America (Mexico to

Panama). The subduction zone can be divided into three systems. The first is the Mexican subduction zone, which is similar to the Chilean subduction zone in some ways (the age of the oceanic crust and the velocity of the Cocos plate relative to South America - Suarez and Sanchez 1996). Further south, the NW-SE trending Middle America trench accommodates the subduction of the Cocos plate beneath Nicaragua, El Salvador and Costa Rica. Ranero and von Huene (2000) have shown that regional changes in the thickness of the overriding Caribbean plate correspond to variations in the old sea floor of the Cocos plate. The authors speculate that the presence of seamounts (isolated submarine mountains) on the seafloor can have a significant effect on the coupling between the overriding and downgoing plates. Husen et al (2002) have found evidence to suggest that two earthquakes in the Gulf of Nicoya (off the west coast of Nicaragua) were caused by increased seismic coupling at the suspected subducted seamounts. Rupture areas calculated from the moment magnitudes of these earthquakes correspond closely to the areas that have been identified as seamounts. The subduction zone is broken briefly by the Southern Panama strike-slip fault zone, just east of the boundary between the Cocos and Nazca plates. Subduction resumes at the Colombia trench, where the Nazca plate is pushed beneath Colombia.

2.2 Seismicity

Earthquakes at the Mexican subduction zone are frequent, although earthquakes larger than 8.2 Mw have not been recorded here. The Petatlan (1974, 7.6 Ms) and Michoacan (1985, 8.1 Ms) earthquakes were the largest recorded in the twentieth century. Suarez and Sanchez (1996) suggest that the reason for the lack of larger events is that the interplate contact is very narrow and sets an upper limit on the magnitude of an earthquake caused by rupture of a single segment of the subduction zone though it would be possible for very large earthquakes to occur if several segments ruptured together. Singh et al (1981) identified the Guerrero and Jalisco segments as zones of high seismic potential. Singh et al (1981) also suggested that potential for a large earthquake on the Michoacan segment was significant and the segment was ruptured in the Michoacan earthquake of 1985.

The Middle American trench is also associated with high levels of seismicity. Although there are no records of an earthquake Ms > 8 occurring in this region, a significant number of earthquakes in the magnitude range 7-8 Ms have been recorded, primarily around the subduction zone. Depths tend to be in the range 15-100 km and earthquakes are generally associated with shallow Quaternary faulting or the Wadati-Benioff zone. Recent damaging earthquakes in the area that are associated with the subduction zone include the January 2001 El Salvador earthquake, which triggered land slips, caused widespread damage and killed 844 people (Bommer et al 2002).

2.3 Seismic hazard and vulnerability

The settlements on the west coast of Mexico are in the zone of highest hazard for this region. This area includes the cities of Culiaca, Mazatlan, Tepic, Colima, Acapulco and Oaxaca. In 2002, 29 people were killed, 300 injured and 10,000 made homeless in and around Colima after the most recent large earthquake (7.6 Ms) on the Mexican subduction zone. Subduction zone earthquakes tend to be strongly felt further west as well and a combination of factors (resonance, basin effects and soil amplification due to very soft lake sediments) led to heavy damage being sustained in Mexico City in the Michoacan earthquake.

Central America is exposed to a wide range of natural hazards, which destroy shelter and infrastructure. Settlements are concentrated on the west coast (especially in El

Salvador and Guatemala), where seismic hazard is highest (a 10% probability of 5.4 m/s^2 being exceeded in 50 years). Poor construction practices and deforestation, which has destabilised slopes, leave the population extremely vulnerable to the next earthquake.

2.4 Possibility for PSInSAR application

The pattern of subduction is reasonably straightforward; the coastal area is for the most part urbanised, and the potential for application of PSInSAR appears to be excellent. The vulnerability of the population to future large earthquakes is high. This is one of the few areas where the ABIC method has already been applied, indicating clearly its suitability. A recent study by Yoshioka et al (2004) succeeded in inverting GPS data in the region of the Guerrero seismic gap and demonstrating that a silent slip event had occurred in 2001-2, equivalent to 7.4 Mw in magnitude, which the authors interpret as likely to postpone a future great earthquake in this area.

Magnitude (Ms)

- ○ 8 and above
- ○ 7 - 7.9
- ○ 6 - 6.9
- ○ 5 - 5.9
- ○ 4 - 4.9

Depth (km)

- ● 0 - 15
- ● 16 - 34
- ● 35 - 50
- ● 51 - 100
- ● 101 - 300
- ● 301 - 500
- ● 501 - 700

Slab Contours

Depth (km)

- 0
- 50
- 100
- 150
- 200
- 250
- 300
- 350
- 400
- 450
- 500
- 550
- 600
- 650

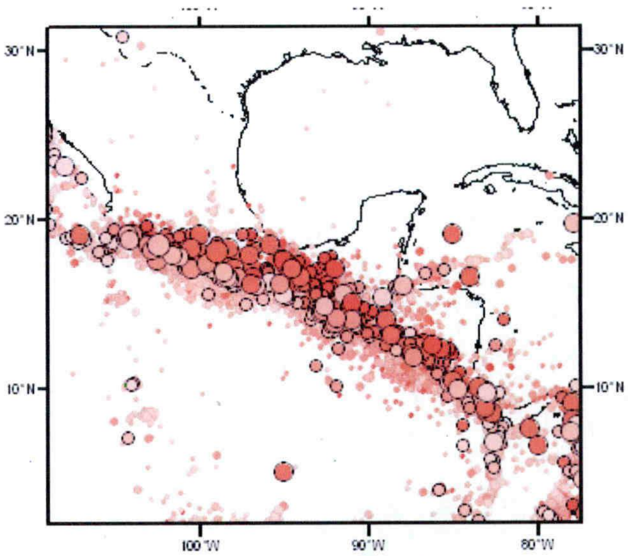
ESRI Population 2002

- ▨ 1
- ▨ 1 - 4
- ▨ 5 - 14
- ▨ 25 - 49
- ▨ 50 - 100
- ▨ 100 - 500
- ▨ 500 - 2,500
- ▨ 2,500 - 5,000
- ▨ 5,000 - 160,345
- ◆ City

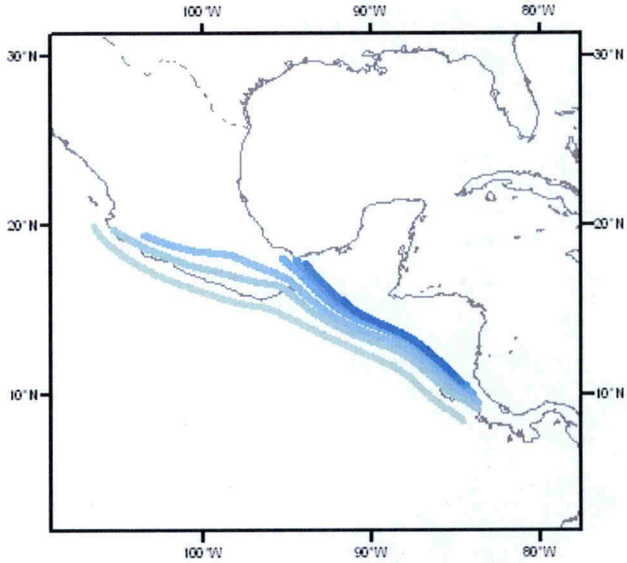
475 yr Hazard

PGA (m/s2)

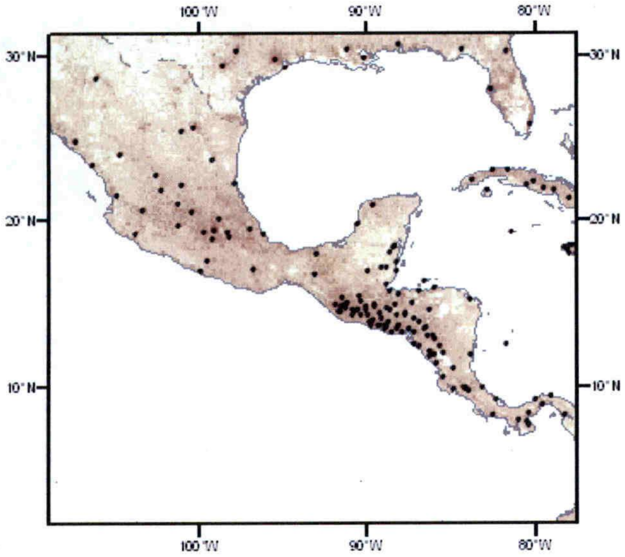
- 🟩 0.0 - 0.2
- 🟩 0.2 - 0.4
- 🟩 0.4- 0.8
- 🟩 0.8 - 1.6
- 🟨 1.6 - 2.4
- 🟧 2.4 - 3.2
- 🟧 3.2 - 4.0
- 🟥 4.0 - 4.8
- 🟥 4.8 - 5.6



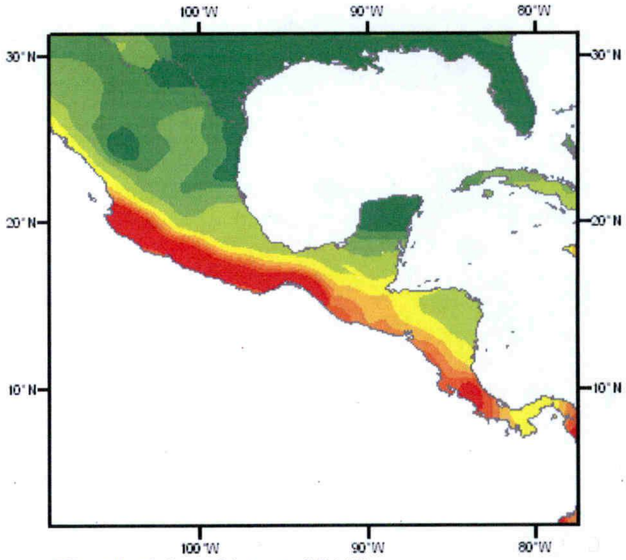
Seismicity (source: BGS World Seismicity Database)



The Subducting Slab: depth contours (source: Sambridge and Gudmundson, 1998)

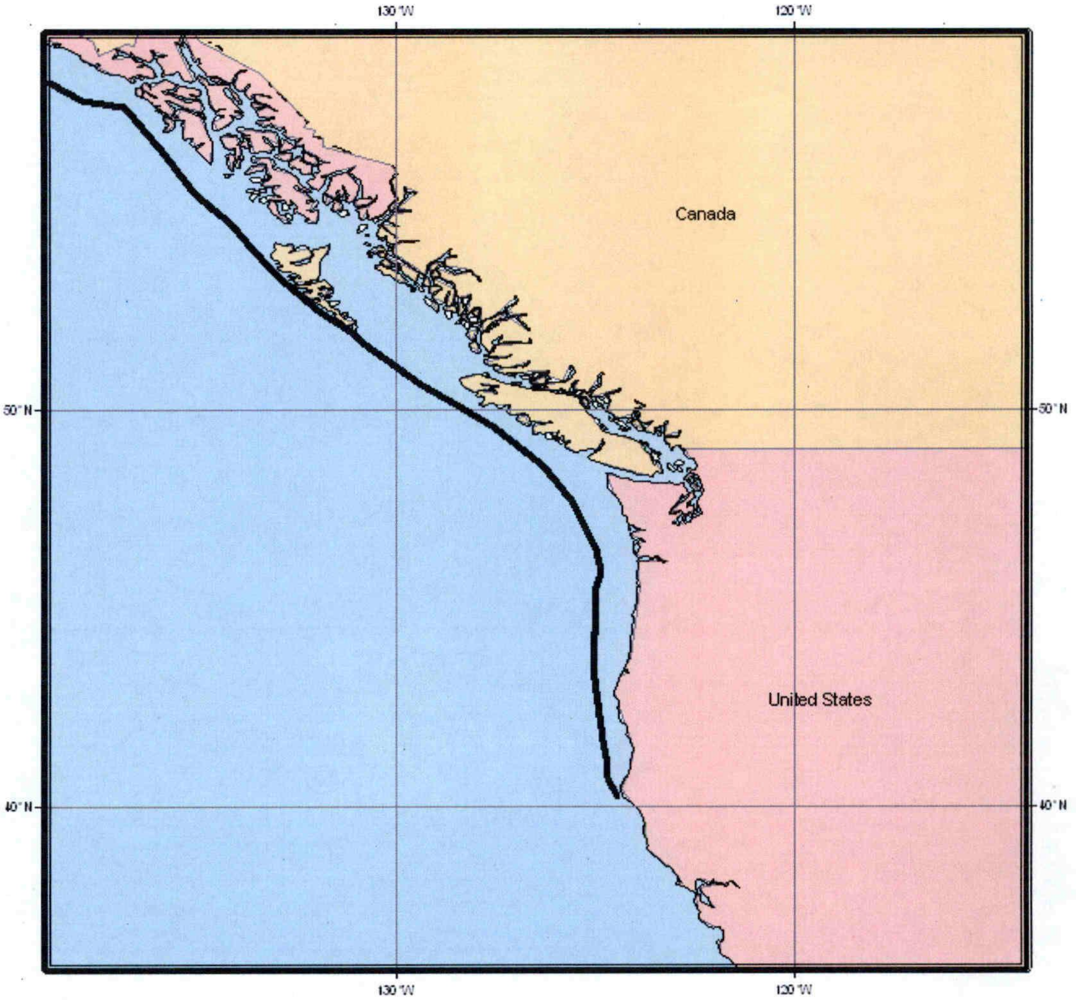


Population distribution for 2002 (source: ESRI)



475 yr seismic hazard (source: GSHAP)

3. Cascadia



The Juan de Fuca and North American plates collide off the west coast of Canada and the United States. Unusally, the subduction zone is associated with only low levels of seismicity. However, the geological record points to great earthquakes occurring here every 500- 600 years.

3.1 Tectonic setting and structure of the subduction zone

The oceanic crust of the Juan de Fuca plate is subducted beneath the more buoyant crust of North America at a rate of about 40 mm/yr in a N68°E direction (De Mets et al 1990). The crust of the subducting plate is relatively young (~10 Ma old) (Heaton and Hartzell 1987, Crosson and Owen 1987, Parsons et al 1998).

The structure of the subduction zone and volcanic arc was not well known, particularly at depths greater than 70 km, until the 1980s when an investigation of Puget Sound was carried out by Crosson and Owen (1987). They found that earthquakes in and around the sound defined an easterly dipping Benioff Zone (10°-12°). North and south of Puget Sound, seismic refraction and reflection data indicated that this angle varies laterally. According to Crosson and Owen (1987), this variation is needed to accommodate the change in the strike of the subduction zone at around 47.5° N.

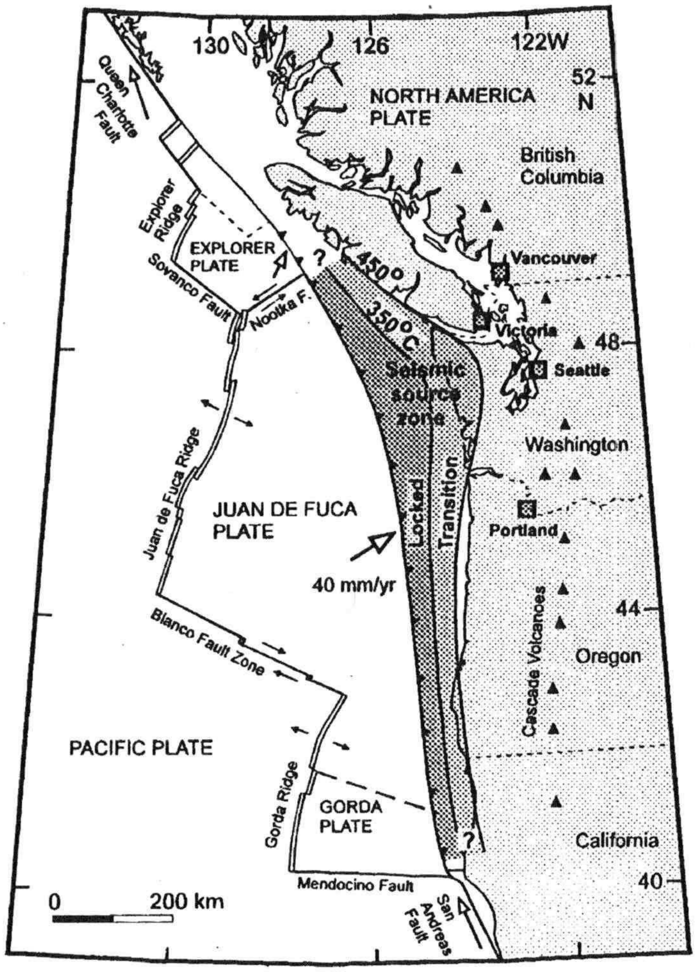


Figure: Tectonics of the Cascadia subduction zone (from Hyndman and Wang 1995).

In a later study, Parsons et al (1998) collected and interpreted seismic data along a transect crossing the subduction zone and volcanic arc. This revealed that the Juan de Fuca plate is about 6 km thick and dips at a shallow angle (0°-5°) at the deformation front. 35 km offshore, this angle steepens to 12°. The angle remains constant to a depth of at least 50 km (75 km inland). Assuming this dip angle, at the longitude of the volcanic arc, volcanism is produced at depths of 60-70 km. If this assumption is correct then the plate is warm enough to produce volcanism at relatively shallow depths.

The Juan de Fuca plate is the relict of a more extensive plate known as the Farallon plate, which lay between the Pacific plate and the North American plate 30 million years ago, and subducted under the North American plate. The central part of the Farallon plate, at the latitude of California, completely subducted between 20 and 30 million years ago, so that the Pacific plate now abuts the North American plate directly along the San Andreas Fault, which has gradually been lengthening as more and more of the Juan de Fuca plate disappears.

Some details of the plate geometry are still a matter of dispute; for instance, at the northern end of the Juan de Fuca plate is an area proposed as a microplate, the

Explorer microplate, which is no longer subducting (Wood and Kienle 1990). However, a study by Kreemer et al (1998) concludes that this is probably not a microplate at all, but part of the North American Plate.

3.2 Seismicity

Levels of seismicity associated with the subduction zone are low compared to other subduction zones, and there is an absence of great earthquakes in the historical record. In 1979, Ando and Balazs suggested that the Juan de Fuca plate was underthrusting the North American plate aseismically. Since then, this hypothesis has been discounted: the Holocene geological record shows evidence for great subduction zone earthquakes or large upper plate earthquakes, which have affected the Washington coastal margin (Parsons et al 1998).

The most recent large earthquake occurred about 300 years ago (Satake et al 1996, Parsons et al 1998). Evidence for it first came to light in Japanese tsunami records. Satake et al (1996) found indications that a far-field tsunami from an unknown source affected several places in Japan on 27-28 January 1700. Satake et al (1996) were able to rule out other Pacific subduction zones as the source of the earthquake and estimated that the tsunami had been produced by an Mw ~ 9 earthquake in Cascadia, which would have ruptured the entire fault zone. The origin time has been worked out as roughly 5h30m on 27 January 1700 GMT. Further confirmation has been found from palaeoseismic studies including coastal land level changes (Atwater 1996) and tree-ring dating (Yamaguchi et al 1997); also from tribal legends.

The recent 28 February 2001 Nisqually earthquake (6.8 Mw) was extensively felt over an area of Washington centred on the south end of Puget Sound, caused one death and only minor damage, but had a significant impact in terms of business interruption. This earthquake occurred within the Juan de Fuca plate and was thus not a true subduction event. Its depth of 52 km contributed to the smallness of the amount of damage.

It is generally agreed that part of the subduction zone is locked (Hyndman and Wang 1995). Hyndman and Wang (1995) suggest that in fact the entire fault zone is locked. The area of the locked zone can be used to constrain the maximum magnitude, and although this zone is narrow, Hyndman and Wang (1995) still expect earthquakes M > 8. The limited width of the locked zone means that it does not extend far inland. As a result, ground motion at major cities like Seattle and Vancouver may be limited for future great subduction zone earthquakes.

3.3 Seismic hazard and vulnerability

Adams et al (1999) estimate that the recurrence interval of great earthquakes in the Cascadian subduction zone is between 500-600 years. According to hazard calculations, there is a 2% probability in 50 years of peak ground accelerations of 45% g and 58% g in Vancouver and Victoria, respectively, being exceeded. The greatest settlement is around Puget Sound (Vancouver and Seattle) and this is also were the greatest concentration of seismicity on the subduction zone is located.

Although much of the Cascadia area consist of mountains and forests, the concentration of high value buildings and industry is considerable, and therefore the economic impact of a large earthquake could be serious. Given that this is a wealthy and highly developed area, it is likely that much construction, especially new construction, is designed to withstand earthquakes and therefore has relatively low vulnerability. Almost certainly, though, there is still a fair amount of older building stock that will be less well constructed. The safety of some transport routes may be at issue. The economic impact of a future large subduction earthquake could be very substantial, especially considering the impact of the 2001 Nisqually earthquake, which was not very severe as regards real physical damage caused.

3.4 Possibility for PSInSAR application

Interest in the application of PSInSAR to Cascadia is likely to be high, on account of the potentially considerable economic impact of a large earthquake in the region. The fact that 300 years have elapsed since the last large subduction earthquake in this region means that already people are speculating as to how far down the development cycle the next large event is. Despite the mountainous nature of much of the area, there should be sufficient urbanisation to obtain a good data set. In fact, the application of the ABIC method for characterising the locked section of the subduction zone has already been attempted for Cascadia by Yoshioka et al (2001) using GPS data; but the GPS data were too few and the results too unconstrained to be useful. The use of PSInSAR should overcome this difficulty. This region is thus rated extremely highly for PSInSAR application.

Subduction zones for PSInSAR

Magnitude (Ms)

- ○ 8 and above
- ○ 7 - 7.9
- ○ 6 - 6.9
- · 5 - 5.9
- · 4 - 4.9

Depth (km)

- ● 0 - 15
- ● 16 - 34
- ● 35 - 50
- ● 51 - 100
- ● 101 - 300
- ● 301 - 500
- ● 501 - 700

475 yr Hazard

PGA (m/s2)

- 🟩 0.0 - 0.2
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- 🟩 0.4 - 0.8
- 🟩 0.8 - 1.6
- 🟨 1.6 - 2.4
- 🟧 2.4 - 3.2
- 🟧 3.2 - 4.0
- 🟧 4.0 - 4.8
- 🟥 4.8 - 5.6

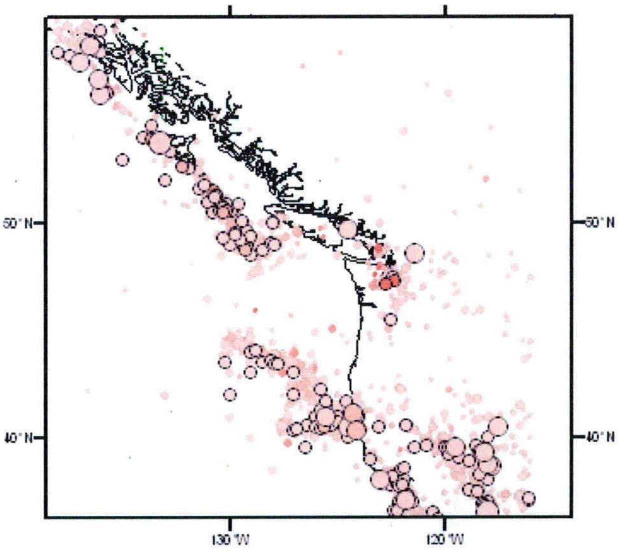
Slab contours

Depth (km)

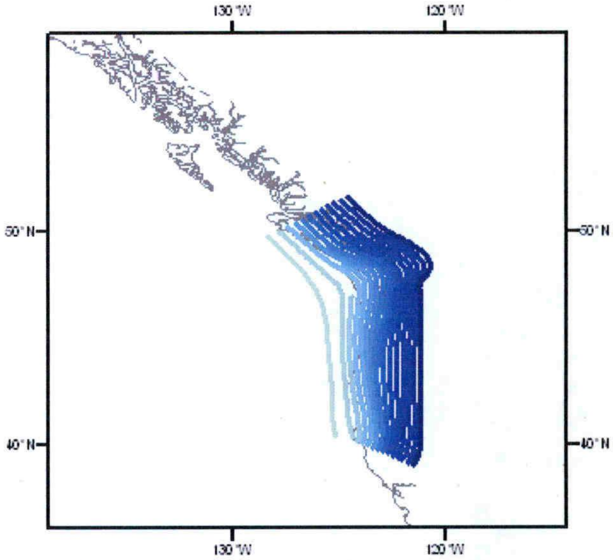
- — 5
- — 10
- — 15
- — 20
- — 25
- — 30
- — 35
- — 40
- — 45
- — 50
- — 55
- — 60
- — 70
- — 80
- — 90
- — 100
- — 110

ESRI Population 2002

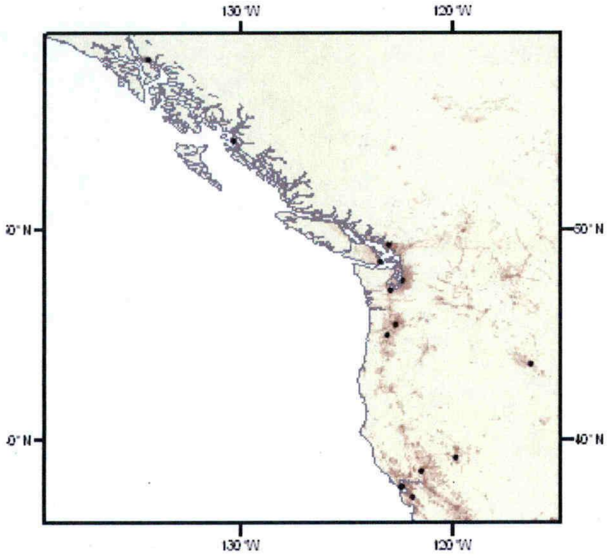
- ▨ 0 - 1
- ▨ 1 - 4
- ▨ 5 - 14
- ▨ 25 - 49
- ▨ 50 - 100
- ▨ 100 - 500
- ▨ 500 - 2,500
- ▨ 2,500 - 5,000
- ▨ 5,000 - 160,345
- ◆ City



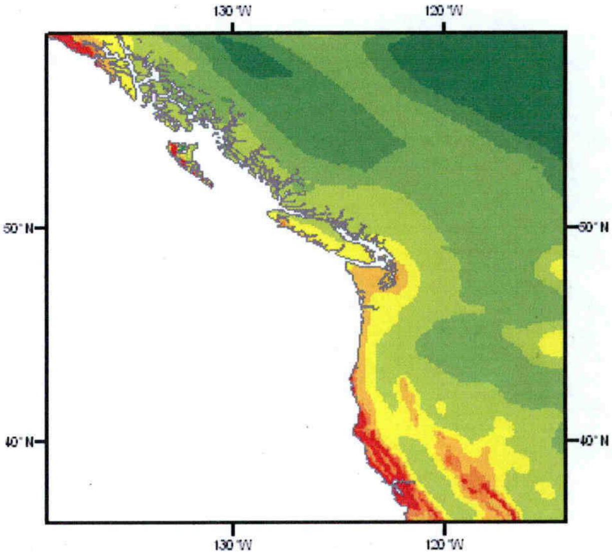
Seismicity (source: BGS World Seismicity Database)



The Subducting Slab depth contours (source: McCrory et al. 2004)



Population distribution for 2002 (source: ESRI)



475 yr seismic hazard (source: GSHAP)

4. South America

In South America, the convergence of the Nazca and South American plates has led to the formation of a large subduction zone characterised by high levels of seismicity and frequent damaging earthquakes.

4.1 Tectonics and structure of the subduction zone

The tectonics of the region have been well-studied. Measurements of plate motions show that the Nazca plate is colliding with the South American plate at a rate of 80 mm/yr in a WNW direction (e.g. De Mets et al 1990), with the oceanic crust of the Nazca plate being subducted beneath the continental crust of South America. Changes in the dip of the upper part of subducting slab (the Wadati-Benioff zone) and the rupture length of great earthquakes suggest that the subduction zone is segmented along its length (e.g. Pardo et al 2002). The most notable change to the slab morphology occurs at around 26°- 33° S, where at intermediate depths the slab flattens and becomes sub-horizontal (Pardo et al 2002). This may be explained by the presence of the Juan Fernandez Ridge (a hot spot seamount chain), the principal bathymetric feature in the region (Pardo et al 2002). In the vicinity of the flat slab, volcanism is thought to have ceased around 9-10 Ma ago whereas south of 33° S, it is still active (Pardo et al 2002). Onshore, Giambiagi et al (2002) have shown that the amount of orogenic shortening of the Andean foreland also appears to be controlled by the dip of the Wadati-Benioff zone.

However, the existence of relatively long stretches of straight subduction interface (up to ~1000 km in length) means that the South American subduction zone is capable of hosting extremely large earthquakes - larger than almost anywhere else on the planet.

4.2 Seismicity

Both the subduction zone and the back-arc are characterised by high levels of seismicity, much of which impacts on the local population. Perhaps the most notorious example is the 1960 9.5 Mw earthquake that devastated the Chilean coast and generated a tsunami that caused fatalities as far away as Hawaii and Japan. In Chile itself, wreckage of boats, houses and trees were picked up by the tsunami and carried inland for up to 2 km. This the largest earthquake ever recorded anywhere in the world. Whilst this earthquake was reasonably shallow, there have been a significant number of damaging, intermediate depth earthquakes (Campos et al 2002). Underthrusting earthquakes (reverse faulting) tend to characterise the shallow part of the subduction zone (< 50 km) (e.g. Delouis et al 1996) whilst deep earthquakes in the Wadati-Benioff zone often have focal mechanisms consistent with tensional stresses acting sub-parallel to the slab causing normal faulting (e.g. Delouis et al, 1996, Campos et al 2002).

The most recent great earthquake in this area was the 23 June 2001 Arequipa (Peru) earthquake (8.4 Mw). This earthquake killed at least 102 and destroyed over 14,000 homes.

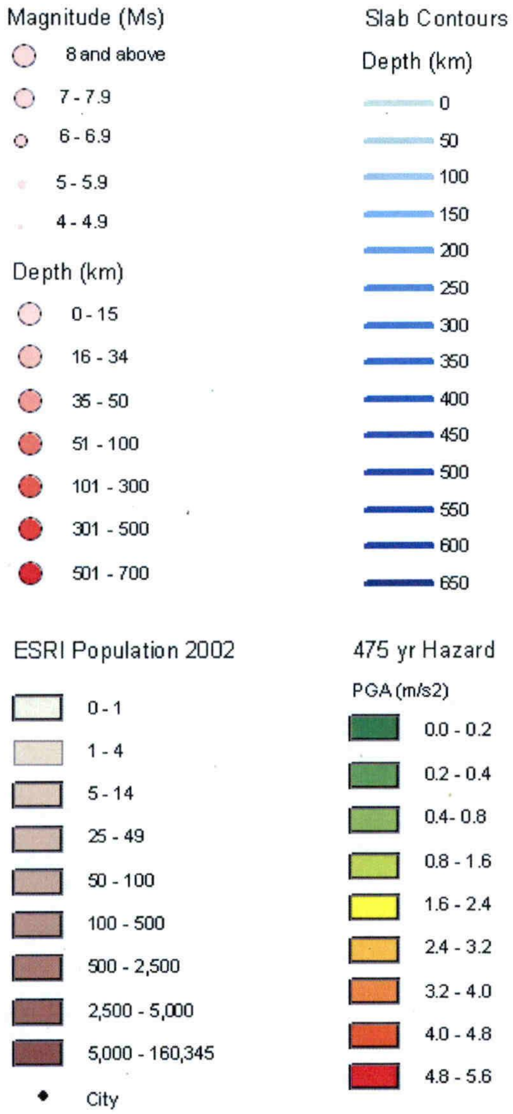
A considerable amount of effort has been put into investigating the seismic gaps along the subduction zone. Nishenko (1985) investigated the seismic gaps along the Chilean and Peruvian margins of South America, since these were also likely to be the areas with the highest seismic potential for large earthquakes. Nishenko (1985) computed the conditional probability of there being a large earthquake in each of ten zones during the period 1984-2004. He found that for this period, probability was highest (99-100%) along the Taltal-Coquimbo segment of the subduction zone (25° and 27°S), which had experienced large earthquakes in 1918, 1939, 1946, 1965-1966, 1978 and 1983. The Los Vilos-Valparaiso-Constitucion gap (32-35°S) was identified as having a probability of 76-99% of a large earthquake in 1984-2004 by Nishenko (1985). These gaps do not necessarily rupture in a single, large earthquake and Korrat and Madariaga (1986) showed that the Los Vilos-Valparaiso-Constitucion gap may have ruptured during several earthquakes.

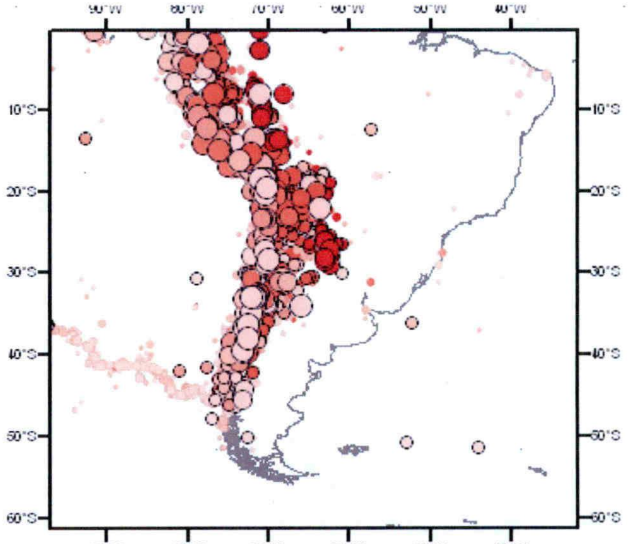
4.3 Seismic hazard and vulnerability

The seismic hazard in South America was calculated for GSHAP (the Global Seismic Hazard Assessment Program) by Shedlock and Tannner (1999). Unsurprisingly, hazard is at its highest close the subduction zone where there is a 10% probability that a peak ground acceleration of at least 4.8 m/s^2 being exceeded in 50 years. Along the west coast of South America, most settlement is concentrated on the coast of Peru and south of Santiago in southern Chile. Although there are a number of very important cities in this area, there are also large tracts of desert and mountain. Building standards vary within the region; many people live in some poverty in adobe houses that are very vulnerable to earthquake damage; but modern industrial developments in the region make earthquake damage a matter of concern to the insurance industry.

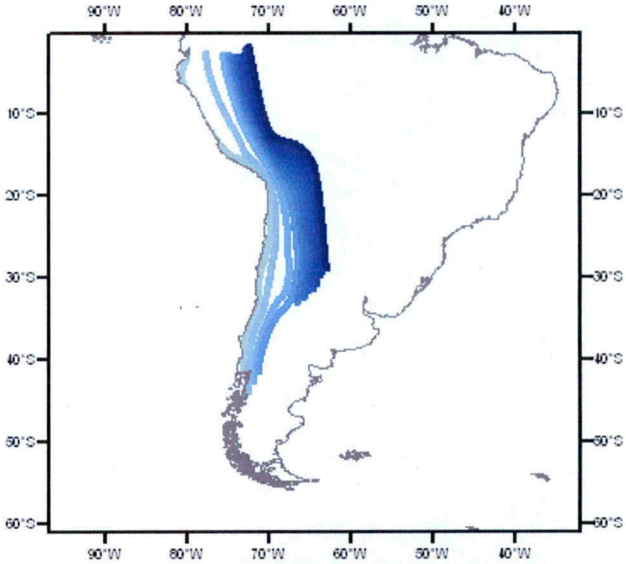
4.4 Possibility for PSInSAR application

The narrowness of the settled coastal strip means that the data available for PSInSAR analysis will be spatially restricted, but should still be sufficient for use. The fact that this is such a long landward subduction zone, some segments of which may be locked and others not, makes it a very interesting area for study. The human and economic implications of large earthquakes in this region provide additional motivation for PSInSAR investigation.

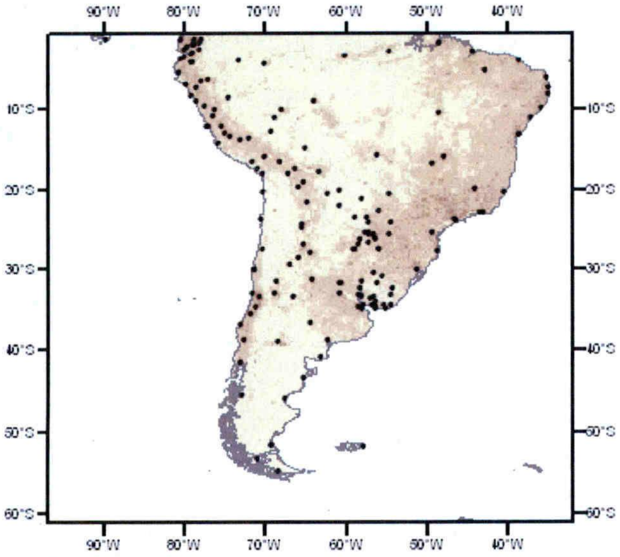




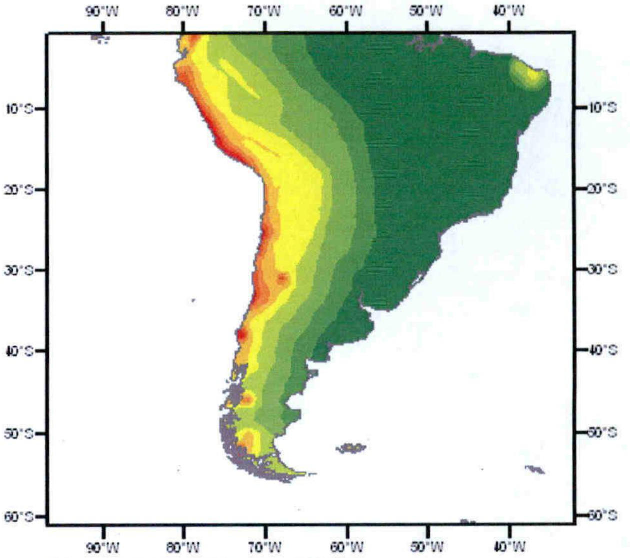
Seismicity (source: BGS World Seismicity Database)



The subducting slab: depth contours (source: Sambridge and Gudmundson, 1998)

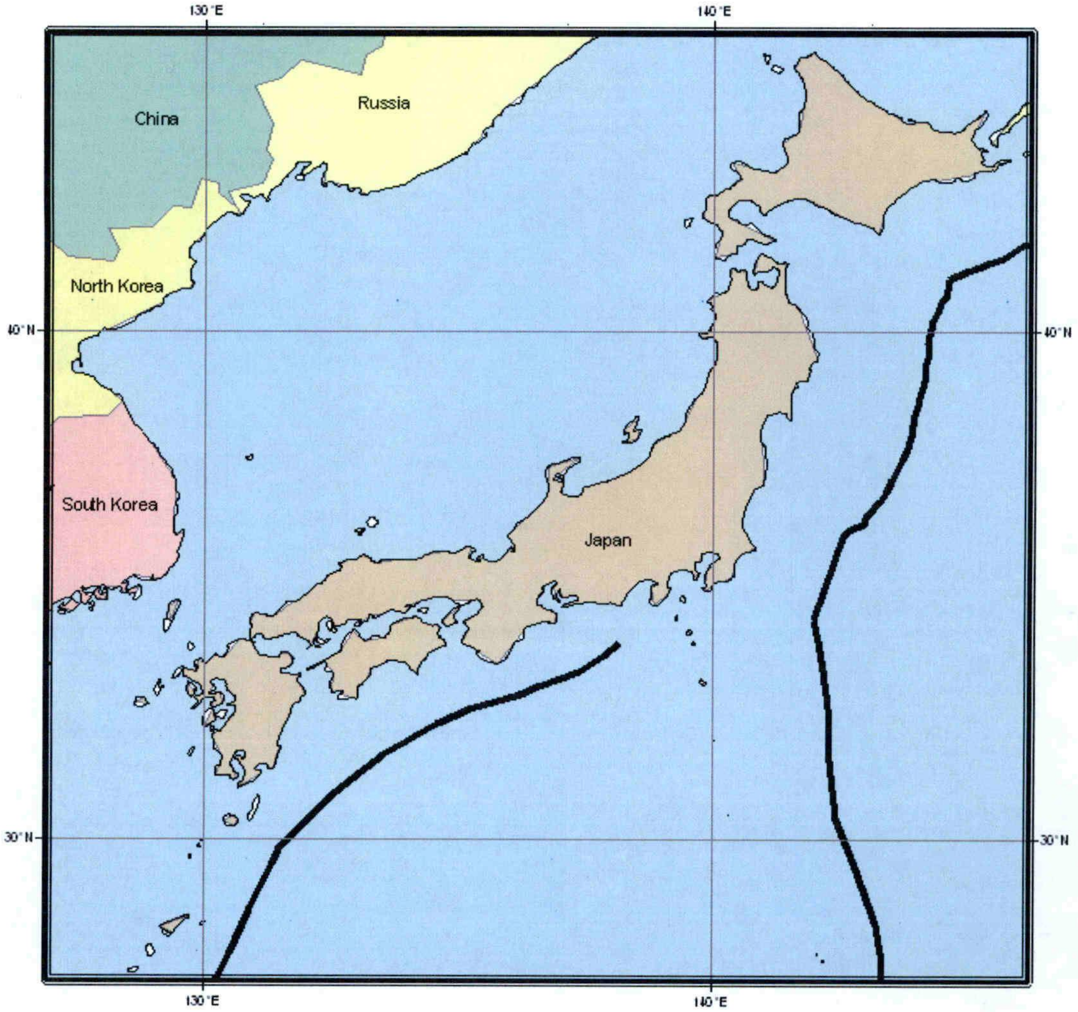


Population distribution for 2002 (source: ESRI)



475 yr seismic hazard (source: GSHAP)

5. Japan



The Japanese islands lie to the west of a region of complex plate interaction. The Pacific plate subducts beneath Eurasia to the north and the Philippine plate subducts beneath Eurasia to the south. Large earthquakes occur frequently.

5.1 Tectonic setting and structure of the subduction zone

Discussion of the plate tectonics of Japan is complicated by differences in opinion as to which plate northern Honshu belongs to, as discussed in Musson and Bommer (2002) following Seno et al (1996). Here we assume the interpretation of Nakamura (1983) that the North American Plate extends as far as the Itoigawa-Shizuoka tectonic line (ISTL).

Japan lies to the west of the interaction of the Philippine Sea, North American and Pacific plates. From the east, the Pacific plate moves roughly westwards at a rate of about 85 mm/yr. Near 35°N, there is a trench-trench-trench triple junction. The western arm (the Sagami trough) acts as the boundary between the Philippine Sea Plate (and continues onshore to the boundary between the North America and Eurasia plate, i.e. the Itoigawa-Shizuoka tectonic line), which is moving in a northwesterly direction, towards Japan, at a rate of 46 mm/yr, and the North American plate. The Philippine Sea and North American plates border onto the Eurasian plate.

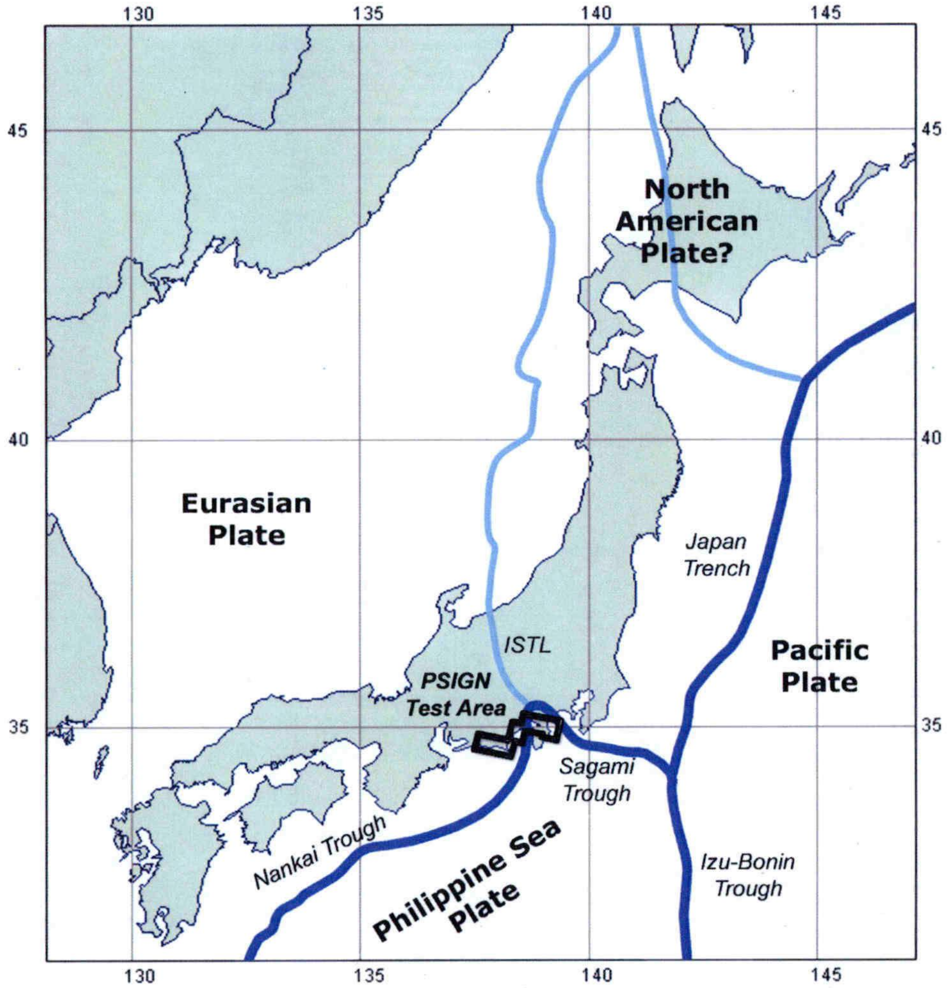


Figure: Tectonics of Japan. Dark blue lines are plate boundaries; lighter blue lines are disputed plate boundaries.

To the north of the Sagami trough, there is a large subduction zone on the eastern margin of the North America plate, where the Pacific plate is subducted, off the east coast of Japan (the Japan trench). To the south of the Sagami trench, there is a third subduction zone where the oceanic crust of the Philippine Sea plate is subducted beneath the continental crust (the Izu-Bonin trough). NE and SW Japan represent two systems of subduction zones (Wang and Suyehiro 1999) and it is convenient to discuss them separately.

5.1.1 NE Japan

Zhao et al (1997) explored the morphology of the subducting slab off the NE coast of Japan, and the implications for seismic coupling in some detail. The results of this study are summarised here. Zhao et al (1997) found that the Pacific plate dips at an angle of less than 10° as it enters the trench. The dip steepens at 30-50 km depth to around 15°-25°. A change in the strike of the trench at about 38°N is associated with a shallower dipping thrust zone and a tendency for larger earthquakes to the north, and a steeper dip angle and smaller earthquakes to the south.

The spatial distribution of interplate seismicity here shows significant variation along the subduction zone implying that seismic coupling at the interplate contact is variable (Sagiya 1999). Zhao et al (1997) suggest that this may be due to seamount subduction (four seamounts have been detected the trench areas around Japan) and segmentation of the oceanic plate.

5.1.2 SW Japan

Here convergence is accommodated in the Nankai trough, which becomes the Suruga Trough at its NE end, off the south coast of Japan. Estimates of the convergence rate range from 17-57 mm/yr and are not well-constrained (Hyndman et al 1995). The plate margin has been identified as a region of high heat flow. This has a significant effect on the down-dip extent of the seismogenic zone, which Hyndman et al (1995) estimate to be about 165 km.

M ~ 8 earthquakes have been documented in this area since AD 684 and indicate that the average repeat time for large thrust earthquakes on the Nankai-Suruga trough is of the order of 120 years. The last major earthquakes in this region were the Nankaido earthquake (8.2 Ms, 1946) and the Tonankai earthquake (8.2 Ms, 1944). From observed repeat times, the next major thrust earthquake is anticipated on the Tokai segment of the trench (Sagiya 1999). The tectonics of this area in particular have been discussed in more detail in previous PSIGN reports, especially Musson and Bommer (2002).

5.2 Seismicity

Numerous large (M > 7) earthquakes have been recorded in and around Japan since 599 AD. The most recent great earthquake to occur was in September 2003 (8.1 Ms), off the coast of Tokachi, Hokkaido, in the north of Japan. The fault plane solution indicates an almost pure thrust mechanism, probably on a shallow dipping fault plane, oriented NNE-SSW. The earthquake caused 12 residential houses to collapse and 501 to be partially destroyed, with one fatality.

5.3 Seismic hazard and vulnerability

Seismic hazard is highly variable over the islands of Japan but is at a maximum on the west coast near the Nankai-Suruga trough, at the boundary between the Eurasian and North America plates in the centre of Japan, around the cities of Tokyo and Yokohama and the SE coast of Hokkaido. Much of the population is concentrated on the east coast in the cities of Matsyan, Osaka, Nagaya, Gifu, Yokohama and Tokyo. These communities are vulnerable to large earthquakes but measures are in place to mitigate the effects. The lack of damage from the great earthquake near Hokkaido in 2003 was commented on by the media, and, while it was partly explained by the distance from shore at which the earthquake occurred, credit should be given to the high standard of construction and earthquake readiness.

On the other hand, the extremely dense concentration of people and capital infrastructure, especially in Honshu, means that there is the potential for large losses, especially those due to economic disruption. The Kobe earthquake in 1995 was the largest single economic loss from any natural disaster ever, estimated at $150 billion. This earthquake was intraplate rather than subduction, and not even very large (M < 7), but did occur directly under a major city. It was very noteworthy after this earthquake that new buildings that complied with the latest Japanese building code survived the earthquake very well, with very little damage, while older construction that was not code-compliant was badly hit. This pattern could well be repeated in future earthquakes.

5.4 Possibility for PSInSAR application

The Tokai region was the locus for the PSIGN test experiment, and the results are discussed elsewhere. The methods that were applied in the test area could very usefully be applied elsewhere, further west (the south coast of Honshu north of the Nankai Trough) and in northern Honshu, especially the area immediately east of the Tokyo conurbation, where the Sagami trough may be locked. This area was studied using the ABIC method by Yoshioka et al (1994). The international economic consequences of a major earthquake loss in Japan could be considerable, and Japan must be considered an important region for future earthquake studies of this type.

Magnitude (Ms)

- ○ 8 and above
- ○ 7 - 7.9
- ○ 6 - 6.9
- • 5 - 5.9
- · 4 - 4.9

Depth (km)

- ● 0 - 15
- ● 16 - 34
- ● 35 - 50
- ● 51 - 100
- ● 101 - 300
- ● 301 - 500
- ● 501 - 700

Slab Contours
Depth (km)

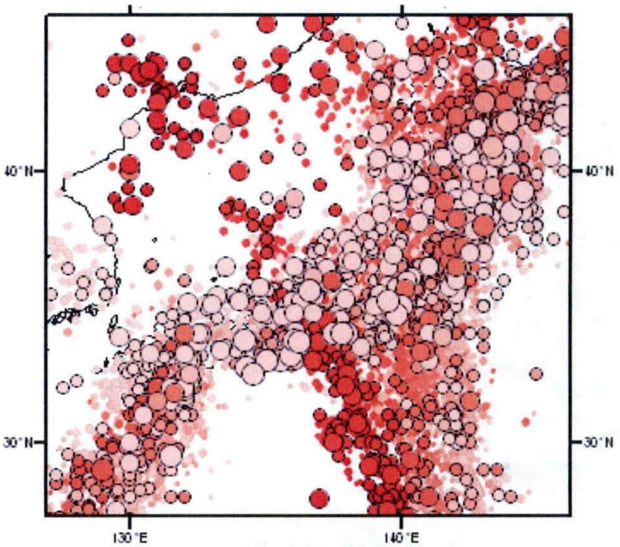
- — 0
- — 50
- — 100
- — 150
- — 200
- — 250
- — 300
- — 350
- — 400
- — 450
- — 500
- — 550
- — 600
- — 650

ESRI Population 2002

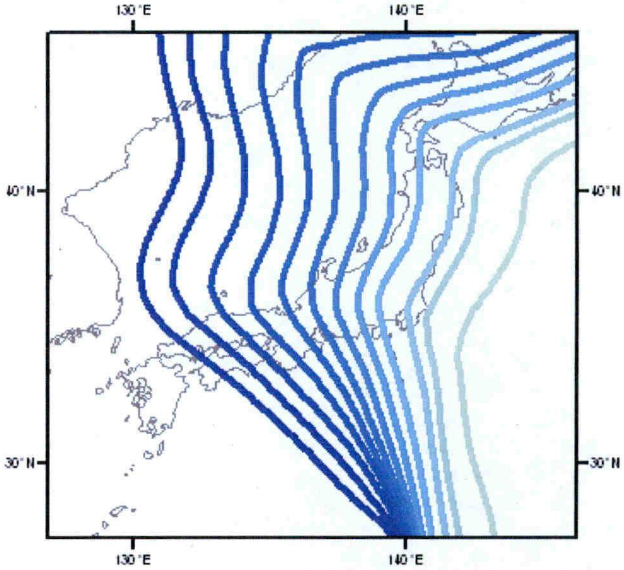
- ▨ 0 - 1
- ▨ 1 - 4
- ▨ 5 - 14
- ▨ 25 - 49
- ▨ 50 - 100
- ▨ 100 - 500
- ▨ 500 - 2,500
- ▨ 2,500 - 5,000
- ▨ 5,000 - 160,345
- ◆ City

475 yr Hazard
PGA (m/s2)

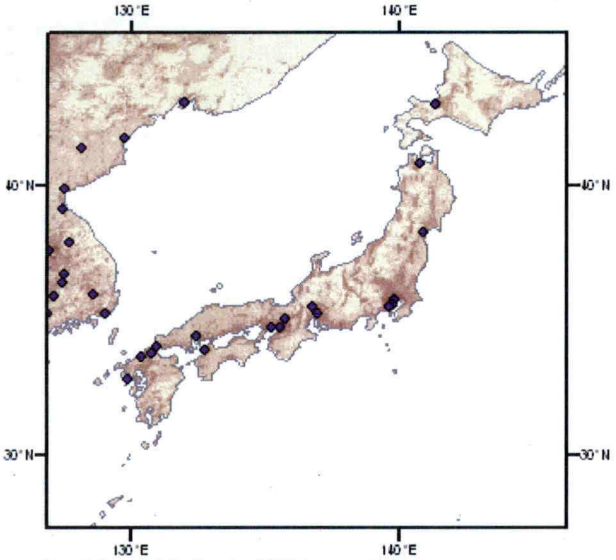
- 🟩 0.0 - 0.2
- 🟩 0.2 - 0.4
- 🟩 0.4- 0.8
- 🟩 0.8 - 1.6
- 🟨 1.6 - 2.4
- 🟧 2.4 - 3.2
- 🟧 3.2 - 4.0
- 🟧 4.0 - 4.8
- 🟥 4.8 - 5.6



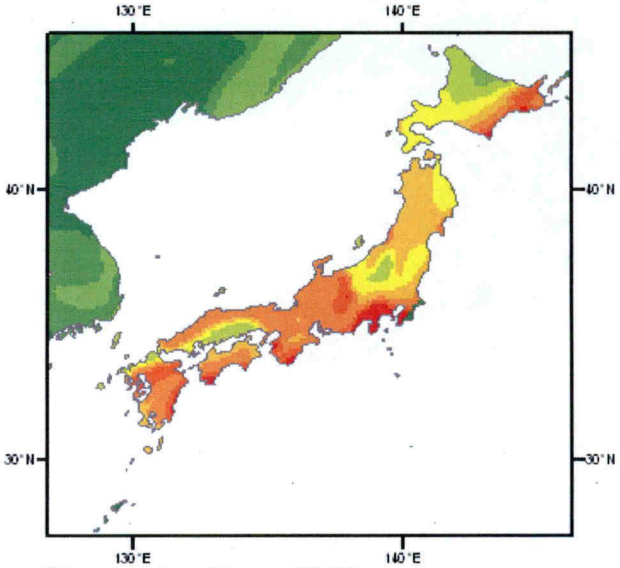
Seismicity (source: BGS World Seismicity Database)



The subducting slab: depth contours (source: Sambridge and Gudmundson, 1998)

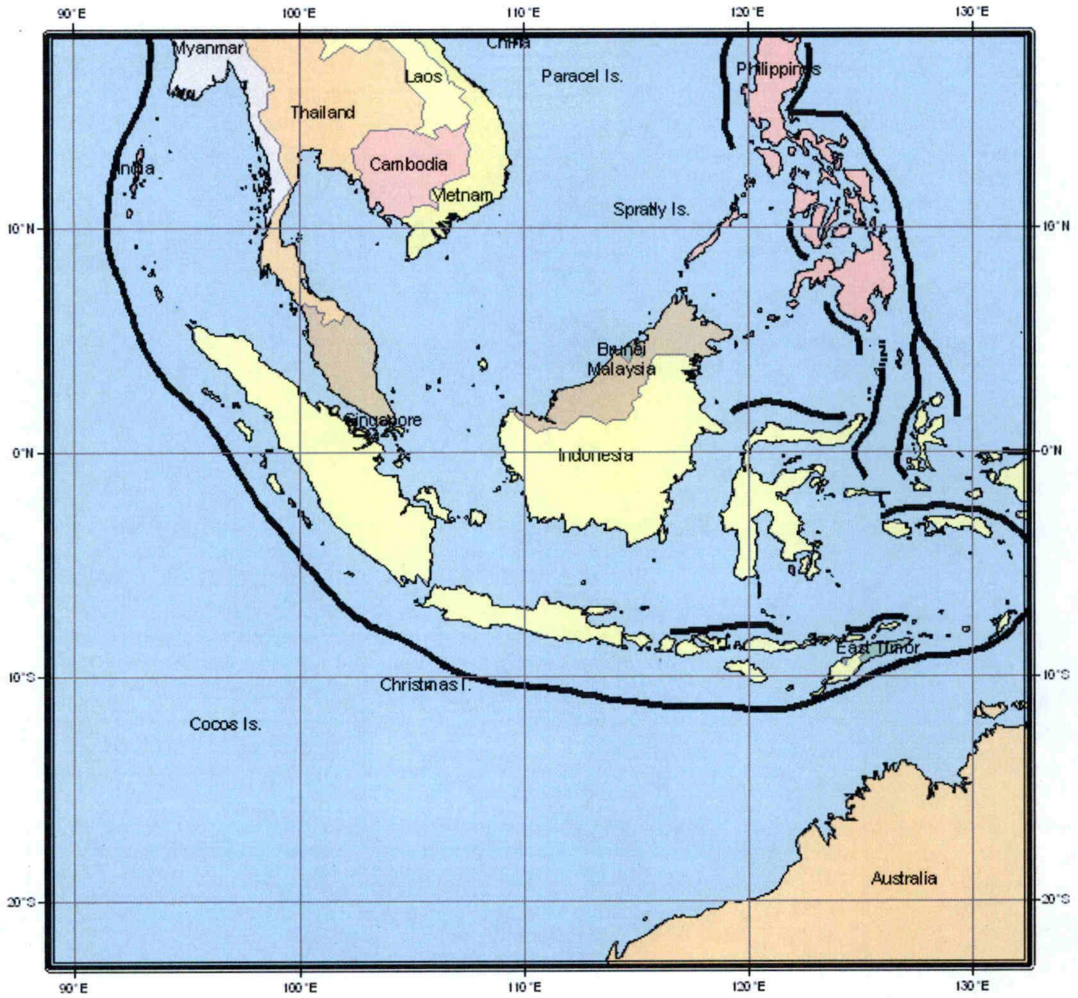


Population distribution for 2002 (source: ESRI)



475 yr seismic hazard (source: GSHAP)

6. Indonesia



The Indo-Australia and Southeast Asia plates collide south of the Indonesian archipelago. The dominant feature of the trench is its curvature, which leads to varying styles of subduction along its length. This in turn causes the seismic potential of sections of the subduction zone to vary. Here we consider chiefly that part of the subduction zone that concerns the large islands of Sumatra and Java.

6.1 Tectonic setting and structure of the subduction zone

The Indo-Australian plate moves in a N10.7°E direction at a rate of 65 mm/yr (De Mets et al 1990) and collides with the Southeast Asia plate to the south of the Indonesian archipelago. Subduction is accommodated along a zone that extends from the Andaman Islands in the northwest to the Banda Arc in the east (Newcomb and McCann 1987). The subduction zone formed in response to the collision of India and Eurasia in the late Eocene, and is thought to have been active since the Oligocene (Kopp et al 2001). The main characteristic of the subduction zone is the curvature of the trench (e.g. Kopp et al 2001). This causes the subduction style to vary along the plate boundary. Near Java, there is frontal subduction, whereas oblique subduction takes place on the Sumatran plate boundary (Newcomb and McCann 1982, 1987, Kopp et al 2001, Rivera et al 2002).

The increasing obliquity of subduction leads to marked differences between the seismotectonic environment of Sumatra, to the west, and Java to the east. At the Sumatra plate boundary, oblique subduction is partitioned into convergent and dextral components (Rivera et al 2002). The convergent component (40-45 mm/yr) is accommodated in the subduction zone whereas the dextral slip component is mainly taken up by two large strike-slip faults (the Sumatra and Mentawai Faults) in the overriding plate (Rivera et al 2002). The Sumatra fault is 2000 km long and forms the backbone of the island and the Mentawai fault lies offshore between the trench and the Sumatra Fault (Rivera et al 2002). Closer to Java, there is simple subduction and the regional tomographic model for this part of the subduction zone shows an area of fast shear wave speed (the down going slab) that extends to a depth of about 1500 km (Gorbatov and Kennett 2003). The age and thickness of the subducted oceanic crust also increases from Sumatra to Java (Newcomb and McCann 1987, Kopp et al 2002) and the width of the plate interface varies along the strike of the subduction zone. Newcomb and McCann (1987) show that there is a broad zone of contact beneath Sumatra, which dips at a shallow angle whereas the zone near Java is narrower and dips more steeply.

6.2 Seismicity

The mode of subduction (seismic vs. aseismic slip) is spatially correlated with changes in tectonic style along the arc, the age of the subducted lithosphere and the convergence rate (Newcomb and McCann, 1987). Besides the greater obliquity of subduction at the Sumatra plate boundary and the subsequent difference in convergence rates, the oceanic crust here is less than 41 Ma old, compared to 147 Ma near Java (Newcomb and McCann 1987). Newcomb and McCann (1987) assess the seismic potential along the Sumatra coast to be high whereas for Java, they assess it to be low. These authors also estimate maximum magnitude to be 8.5-9.0 and 7.3 for Sumatra and Java, respectively.

The majority of large and great earthquakes associated with the Sumatra subduction zone are located in the fore-arc (Newcomb and McCann et al 1987). Sea level fluctuations recorded in massive coral heads indicate periods of submergence and uplift, presumably due to significant earthquakes (Natawidjaja et al 2000). In the 19th century, much or all of the Sumatra plate boundary was ruptured in major earthquakes, in 1833 and 1861 (Newcomb and McCann 1982). The most recent great earthquake (7.9 Ms) occurred off the south coast of Sumatra in June 2000 (on a north-south trending strike-slip fault) and caused widespread damage and fatalities on the island. In contrast, the historical earthquake record for Java contains only a few large events, one of which was tsunamigenic (Newcomb and McCann 1982).

6.3 Seismic hazard and vulnerability

As one would expect, seismic hazard is highest on the south coast of Sumatra, nearest the fore-arc. The 475-year hazard varies from 0.8 m/s^2 on the north coast to 4.0 m/s^2 in the south. The islands are densely populated. On Sumatra, the cities of Banda Aceh, Padang, Bengkulu and Tanjungkarang-Telubethung are situated closest to the subduction zone and in the region of highest seismic hazard. Seismic hazard is also high on the western tip of Java, where Jakarta and Bedung are situated. The very high population density means that a large earthquake has the possibility to cause heavy loss of life in crowded cities, where construction is generally not of the highest quality.

6.4 Possibility for PSInSAR application

The high population density in Java, and the classic nature of the subduction to the south of the island, would make it a good case for PSInSAR investigation. On the other hand, it seems less likely that great earthquakes will occur here. In the case of Sumatra, the geography of human settlement suggests that data sets will not be quite so good, and the tectonics are more complex. On the whole, this region is a possibility, but perhaps not a high priority.

Magnitude (Ms)

- ○ 8 and above
- ○ 7 - 7.9
- ○ 6 - 6.9
- · 5 - 5.9
- · 4 - 4.9

Depth (km)

- ● 0 - 15
- ● 16 - 34
- ● 35 - 50
- ● 51 - 100
- ● 101 - 300
- ● 301 - 500
- ● 501 - 700

Slab Contours

Depth (km)

- — 0
- — 50
- — 100
- — 150
- — 200
- — 250
- — 300
- — 350
- — 400
- — 450
- — 500
- — 550
- — 600
- — 650

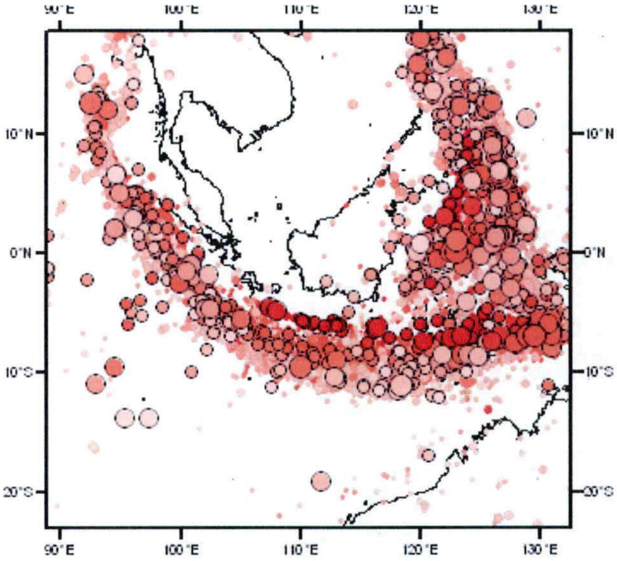
ESRI Population 2002

- ▨ 0 - 1
- ▨ 1 - 4
- ▨ 5 - 14
- ▨ 25 - 49
- ▨ 50 - 100
- ▨ 100 - 500
- ▨ 500 - 2,500
- ▨ 2,500 - 5,000
- ▨ 5,000 - 160,345
- ◆ City

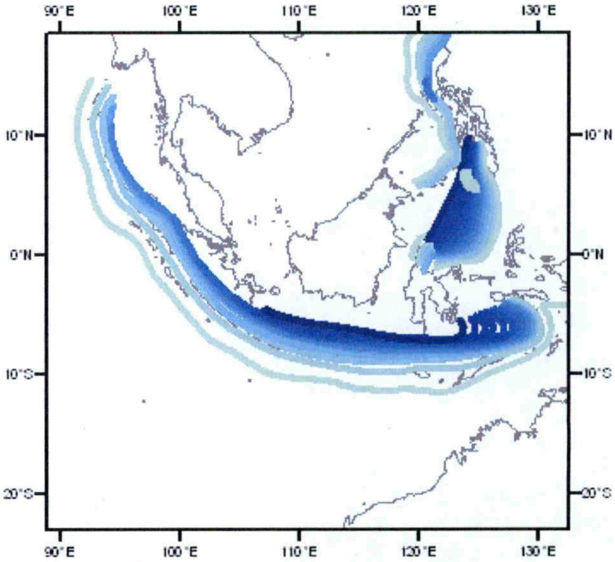
475 yr Hazard

PGA (m/s2)

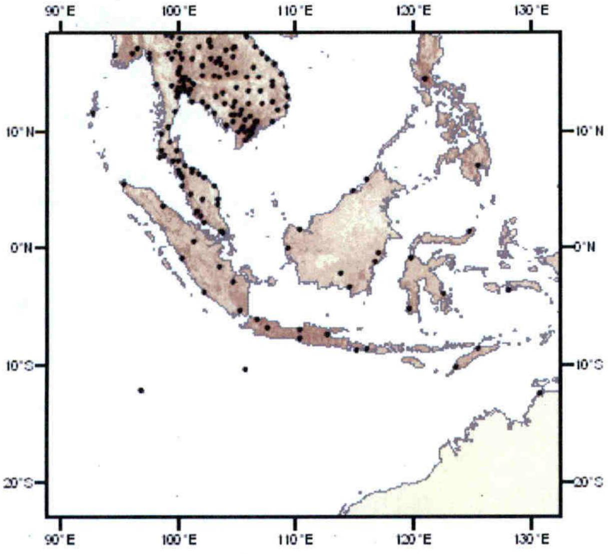
- 🟩 0.0 - 0.2
- 🟩 0.2 - 0.4
- 🟩 0.4- 0.8
- 🟩 0.8 - 1.6
- 🟨 1.6 - 2.4
- 🟧 2.4 - 3.2
- 🟧 3.2 - 4.0
- 🟧 4.0 - 4.8
- 🟥 4.8 - 5.6



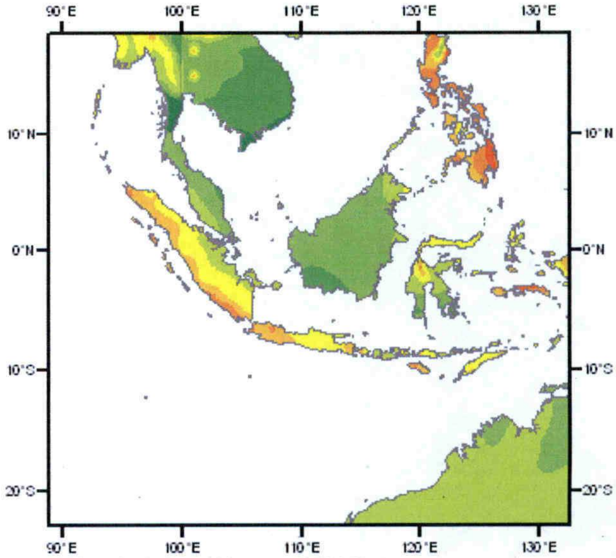
Seismicity (source: BGS World Seismicity Database)



The subducting slab: depth contours (source: Sambridge and Gudmundson, 1998)

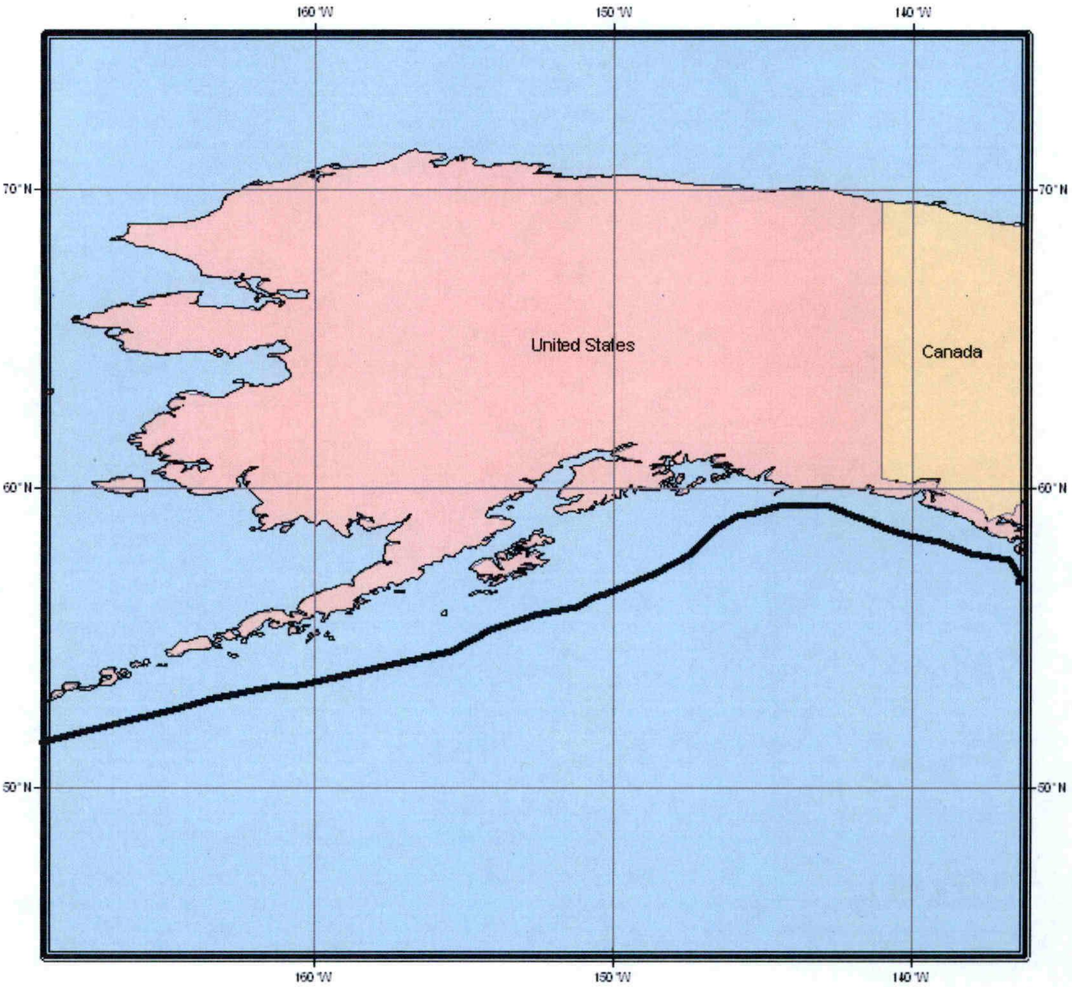


Population distribution for 2002 (source: ESRI)



475 yr seismic hazard (source: GSHAP)

7. Alaska



The Pacific plate is underthrusting the continental crust of North America at the latitude of the Aleutian Islands. The area is considered by some to be one of the world's most active plate boundaries and has a history of great earthquakes.

7.1 Tectonic setting and structure of the subduction zone

The Pacific plate is being subducted beneath the North America plate at the latitude of southern Alaska and the Aleutian islands, at a rate of 57 mm/yr in a northerly direction (De Mets et al 1990). At the Aleutian Islands, the direction of motion of the Pacific plate is perpendicular to the trench axis, leading to normal subduction. The situation is more complex near Alaska, where subduction is oblique (Ratchkovski and Hansen 2002).

Nishenko and Jacob (1999) identified five tectonic regimes at the Alaskan-Aleutian plate boundary. From east to west these are: 1) strike-slip faulting in the Queen Charlotte-Fairweather Fault Zone, 2) a transition between strike-slip faulting and underthrusting in the eastern Gulf of Alaska, 3) continental style convergence in southern Alaska, 4) island arc subduction at the Aleutian islands and 5) transform faulting in the west Aleutian-Kommandorski islands. Above the Alaskan part of the subduction zone, the overlaying crust is split into three blocks (Ratchkovski and Hansen 2002). There is evidence to suggest that a surface discontinuity between two of the bocks persists at depth as a tear in the subducted plate (Ratchkovski and Hansen 2002).

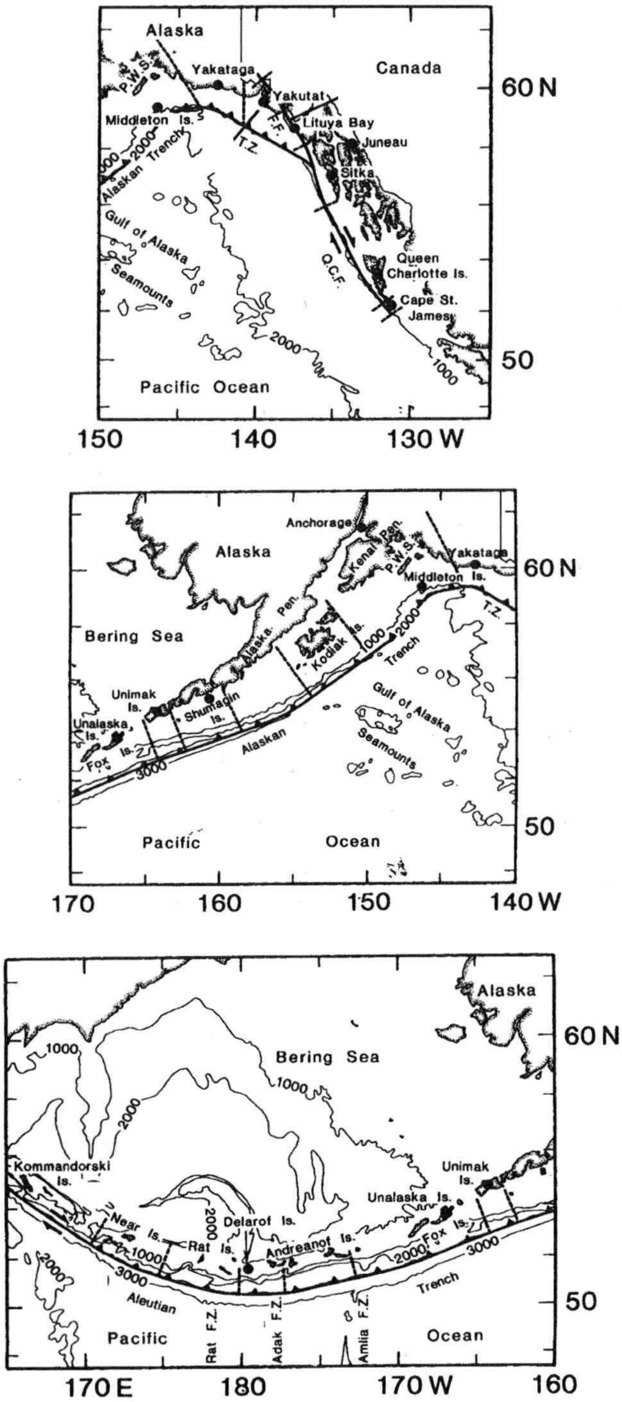


Figure: Sections of the Alaskan-Aleutian subduction zone (from Nishenko and Jacob 1999)

7.2 Seismicity

Seismicity is dominated by Benioff Zone activity within the subducted plate (Stephens et al 1984, Doser et al 2002), with relatively few earthquakes occurring on the megathrust; however, when these occur they can be very large. The great earthquake of 1964 had a rupture plane with an area equivalent to most of California. Seismicity within the North American plate is also low and in the upper plate offshore, earthquakes tend to be located beneath arched regions of crust between sedimentary basins (Doser et al 2002). However, sporadic large earthquakes within the North American Plate also occur, notably the 7.9 Mw Denali earthquake of 3 November 2002, which was a strike-slip event.

The subduction zone is segmented with respect to seismicity. These segments are thought to be at different stages in the seismic cycle. Bule et al (1994) identified the segments at the Alaskan Peninsular and Shumagin Islands as being closest to the end of the seismic cycle, and therefore potential sites for future great earthquakes. These segments were ruptured almost simultaneously (days apart) in August 1788 and April 1847/1848. Rupture on these segments in the near future would be consistent with the east to west progression of great earthquakes (from east to west: Queen Charlotte Islands, 8.1 Ms, 1958; Litya Bay, 8.2 Ms, 1958; Prince William Sound, 9.2 MW, 1964) that has been observed. Savage and Lisowski (1986) also identified the Yakataga seismic gap as a zone with great potential for a large earthquake. This segment is bounded by the rupture area of the 1964 earthquake to the west and the rupture area of an earthquake on the Fairweather Transform Fault (1958, 7.7 MW) to the east.

The largest earthquake to occur here was the 1964 Prince William Sound event (9.2 Mw). Rupture initiated in Prince William Sound and propagated SW, reaching a total length of 800 km with maximum surface displacements of more than 10 m (Doser et al 2002). This earthquake is the second largest ever to be recorded anywhere in the world. Current seismicity is located outside the regions of highest slip determined for the 1964 earthquake and the locked regions may serve to indicate areas that will rupture in future moderate magnitude earthquakes (Santini et al 2003).

Some predictability of large earthquakes in the region has been claimed - at least in the case of the 7.9 Mw earthquake in the Central Aleutians on 10 June 1996 (Purcaru 1996).

7.3 Seismic hazard and vulnerability

Bule et al (1994) evaluated the conditional probability of the recurrence of a large earthquake for different segments of the subduction zone. The Shumagin Islands, Fox Islands, Delarof Islands of the Alaska-Aleutian arc were identified as having the greatest probability of a large earthquake during the period 1994-2004. Seismic hazard assessments for southern Alaska reflect the high levels of seismicity at the plate margin. Although most of the region is sparsely populated, the cities of Anchorage and Seward, on the south coast, are located within a zone of high seismic hazard (3.2-4.8 m/s^2). The city of Anchorage was badly damaged in 1964. Modern construction is likely to have a high degree of earthquake resistance through good design. The survival of the Trans-Alaskan pipeline during the Denali earthquake was a showcase for good antiseismic design. Despite the fact that the pipeline ran right across the fault rupture, damage was minor and the integrity of the pipeline was not threatened.

7.4 Possibility for PSInSAR application

Tectonically, the area is certainly suitable for PSInSAR analysis, and although the amount of human exposure is low, the high degree of economic development of the USA to some degree counterbalances this. However, the fact that most of the area is wilderness or sea means that it is very unlikely that suitable datasets could be obtained.

Magnitude (Ms)

- ○ 8 and above
- ○ 7 - 7.9
- ○ 6 - 6.9
- ● 5 - 5.9
- ● 4 - 4.9

Depth (km)

- ● 0 - 15
- ● 16 - 34
- ● 35 - 50
- ● 51 - 100
- ● 101 - 300
- ● 301 - 500
- ● 501 - 700

Slab Contours

Depth (km)

- ▬ 0
- ▬ 50
- ▬ 100
- ▬ 150
- ▬ 200
- ▬ 250
- ▬ 300
- ▬ 350
- ▬ 400
- ▬ 450
- ▬ 500
- ▬ 550
- ▬ 600
- ▬ 650

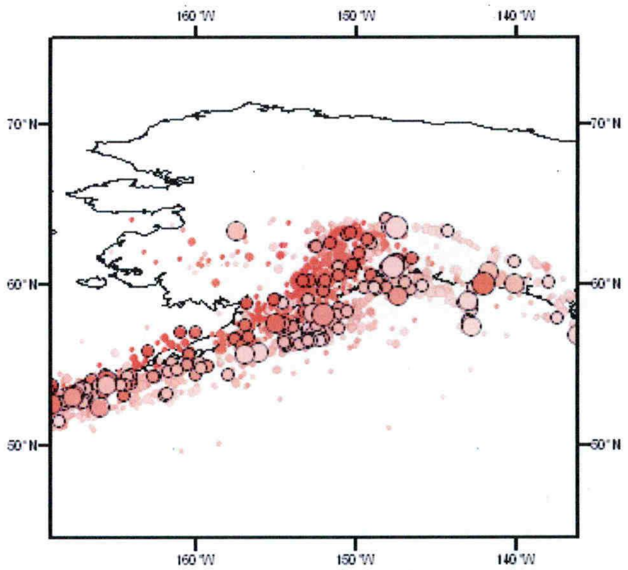
ESRI Population 2002

- ▭ 0 - 1
- ▭ 1 - 4
- ▭ 5 - 14
- ▭ 25 - 49
- ▭ 50 - 100
- ▭ 100 - 500
- ▭ 500 - 2,500
- ▭ 2,500 - 5,000
- ▭ 5,000 - 160,345
- ◆ City

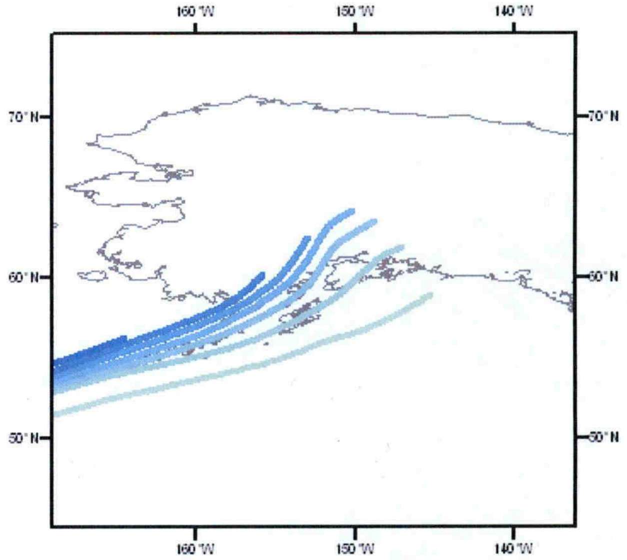
475 yr Hazard

PGA (m/s2)

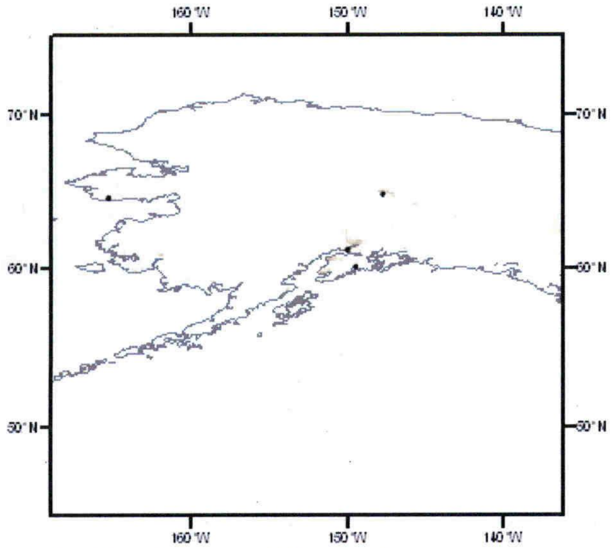
- 🟩 0.0 - 0.2
- 🟩 0.2 - 0.4
- 🟩 0.4- 0.8
- 🟩 0.8 - 1.6
- 🟨 1.6 - 2.4
- 🟧 2.4 - 3.2
- 🟧 3.2 - 4.0
- 🟧 4.0 - 4.8
- 🟥 4.8 - 5.6



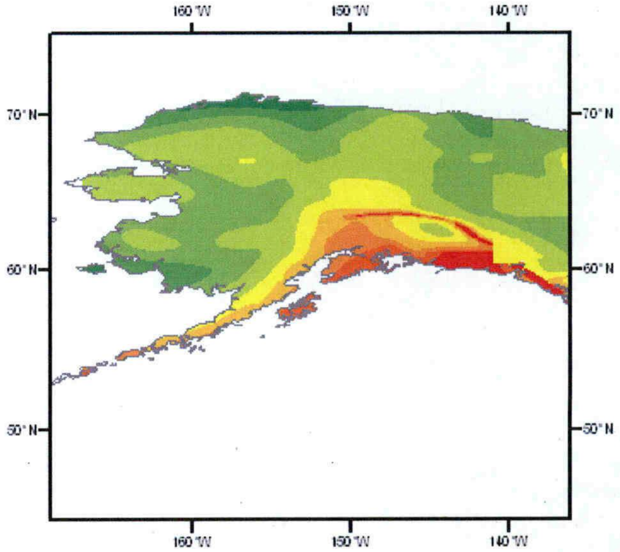
Seismicity (source: BGS World Seismicity Database)



The subducting slab: depth contours (source: Sambridge and Gudmundson, 1998)

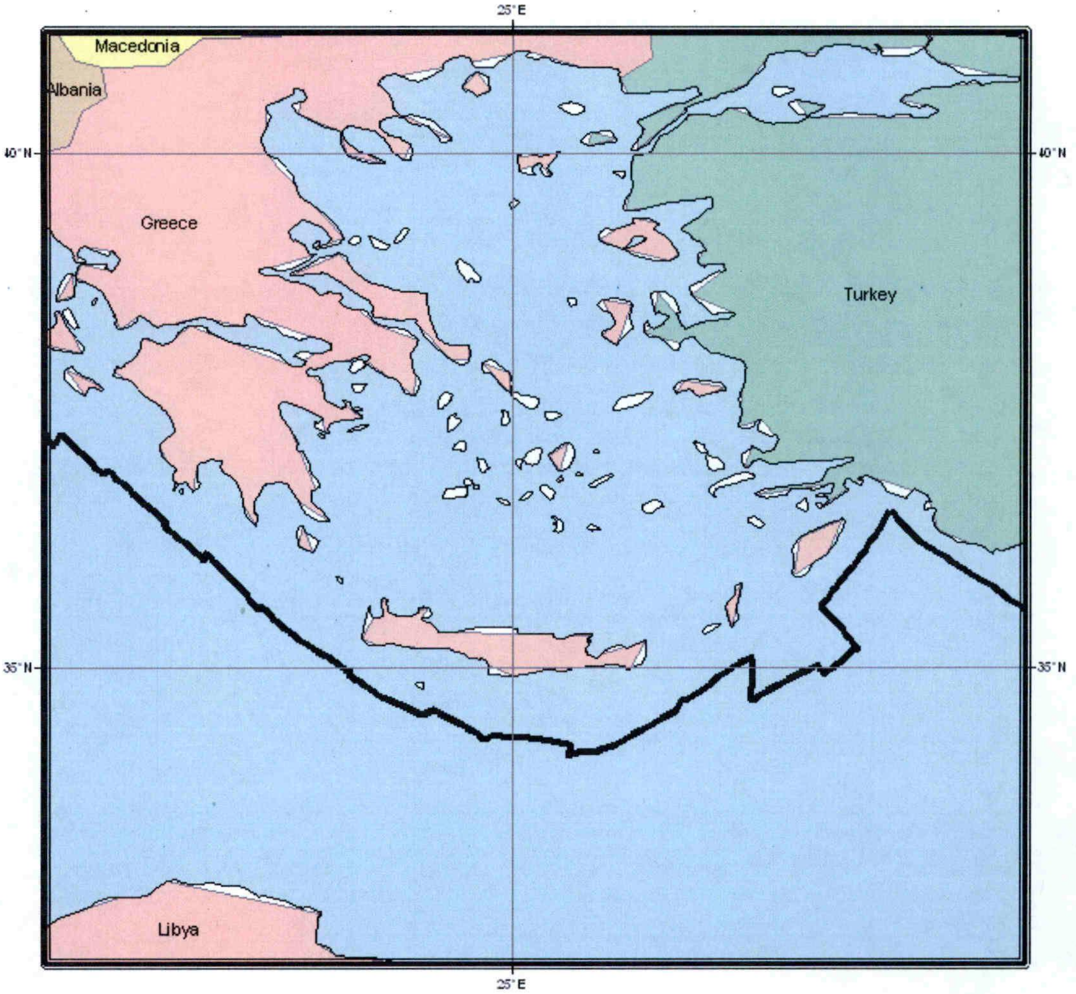


Population distribution for 2002 (source: ESRI)



475 yr seismic hazard (source: GSHAP)

8. The Aegean



Convergence between the Eurasian and African plates, initiated during the Cretaceous, has lead to the formation of the Hellenic subduction zone, which is now associated with moderate-magnitude, but mostly intermediate depth seismicity.

8.1 Tectonic setting and structure of the subduction zone

Various researchers, e.g. Taymaz et al (1991), have identified three large-scale tectonic processes operating in and around the Aegean:

1. The effects of the westward motion of Turkey (relative to Eurasia).
2. Continental collision of the Adriatic coast of Greece and Albania and the Adriatic-Apulia platform.
3. Convergence between the Eurasian and African plates, accommodated by subduction at the Hellenic trench.

At the longitude of the Hellenic Trench, convergence between the Africa and Eurasia plates occurs at a rate of about 10 mm/year (Argus et al 1989). For about 200 km from the trench, the African plate dips gently beneath Greece. Under the Gulf of

Corinth at a depth of around 150 km, the angle of dip increases and it plunges further into the mantle, possibly remaining intact to depths of up to 600 km (Hatzfeld 1994).

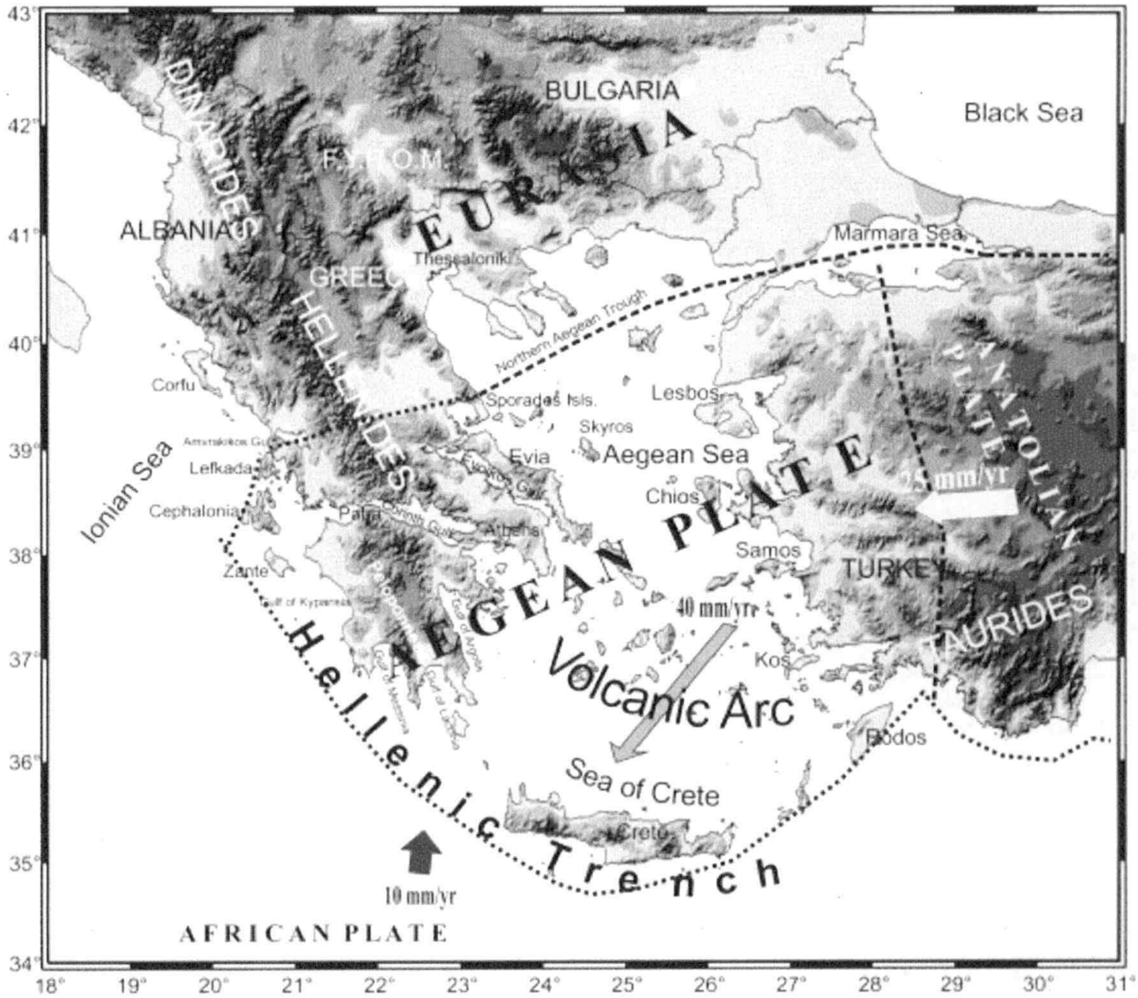


Figure: Plate motions in the Aegean area (from Kiratzi and Louvari 2003).

8.2 Seismicity

Intermediate depth earthquakes at the Aegean subduction zone define an 'amphitheatre' shaped Benioff zone and large earthquakes here constitute a significant threat to southern Greece (Papazachos 1990). The three largest earthquakes (8 < Ms < 8.2) were in 365 AD, 1856 and 1926, each causing widespread destruction on Crete and Rhodes (Papazachos 1990). Depths, on the whole, are difficult to ascertain from historical information, especially for the offshore earthquakes. For the 365 and 1856 events, estimates of depth are not available but both earthquakes were tsunamogenic, which provides some constraint. The depth of the 1926 earthquake (8.2 Ms) was estimated to be about 100 km by Papazachos and Papazachou (1997) and is the largest earthquake to have ever occurred in the Aegean.

Seismic gaps have not been identified along the Aegean subduction zone as they have for others but Baker et al (1997) have shown that there is a discrepancy between seismic energy release and the amount of shortening, which can be explained by partially aseismic subduction at the Hellenic trench.

8.3 Seismic hazard and vulnerability

Considering the map of seismicity for the Aegean, it is unsurprising that the peak ground acceleration hazard for a 475 year return period is high for much of the region. As a whole, population density in the Aegean is not high. The largest islands near the subduction zone are Crete (where the hazard varies from 2.4 to 3.2 m/s^2), to the south, and Rhodes, to the southeast (similar hazard values). A study by Papaioannou and Papazachos (2000) considers the hazard to be particularly high when using a time-dependent approach that takes into account the relative quiescence of the subduction front during the second half of the 20th century.

Much of the settlement on Crete is concentrated on the north coast of the island and includes Hania, Rethimno, Iraklio, Agios Nikolaos and Sitia. Rhodes is also well populated, as are the Peloponnese, to the west of the subduction zone. Typical traditional Mediterranean housing styles are not especially resistant to earthquakes, but since the first issue of the Greek Seismic Code, this area has been discriminated as having the highest earthquake risk, and the local authorities take seismic safety of buildings very seriously. This includes active measures to protect historical buildings.

8.4 Possibility for PSInSAR application

Greece is a case of special interest, as being the most significant subduction zone in Europe. However, the possible application of PSInSAR is restricted due to the island geography. It might be possible to image a locked zone under Crete, but not if it were between Crete and Rhodes.

Magnitude (Ms)

- ○ 8 and above
- ○ 7 - 7.9
- ○ 6 - 6.9
- ○ 5 - 5.9
- ○ 4 - 4.9

Depth (km)

- ● 0 - 15
- ● 16 - 34
- ● 35 - 50
- ● 51 - 100
- ● 101 - 300
- ● 301 - 500
- ● 501 - 700

Slab Contours

Depth (km)

- — 0
- — 50
- — 100
- — 150
- — 200
- — 250
- — 300
- — 350
- — 400
- — 450
- — 500
- — 550
- — 600
- — 650

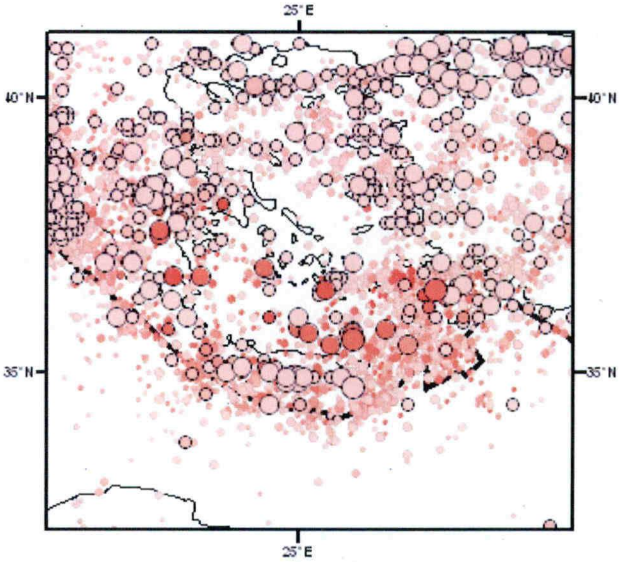
ESRI Population 2002

- ■ 0 - 1
- ■ 1 - 4
- ■ 5 - 14
- ■ 25 - 49
- ■ 50 - 100
- ■ 100 - 500
- ■ 500 - 2,500
- ■ 2,500 - 5,000
- ■ 5,000 - 160,345
- ◆ City

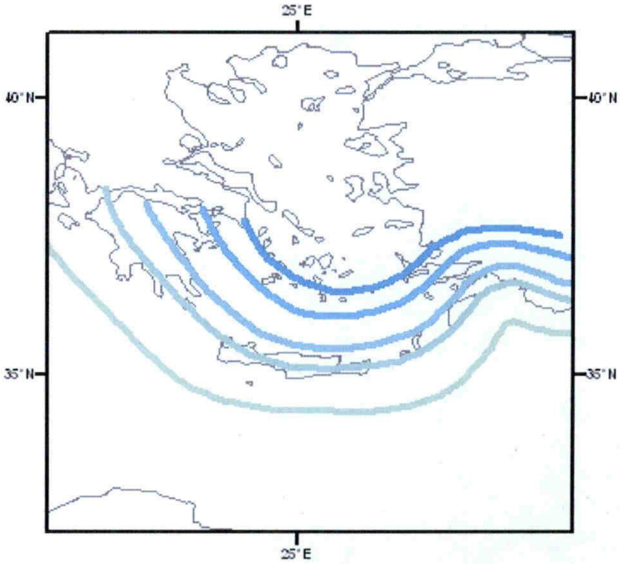
475 yr Hazard

PGA (m/s2)

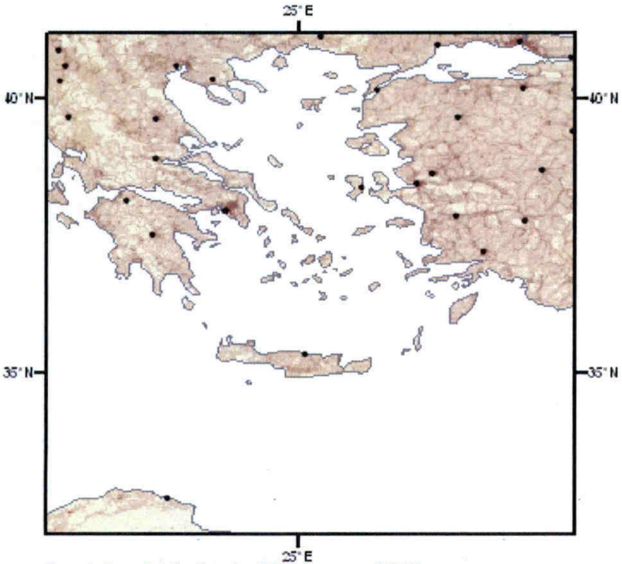
- 🟩 0.0 - 0.2
- 🟩 0.2 - 0.4
- 🟩 0.4- 0.8
- 🟩 0.8 - 1.6
- 🟨 1.6 - 2.4
- 🟧 2.4 - 3.2
- 🟧 3.2 - 4.0
- 🟥 4.0 - 4.8
- 🟥 4.8 - 5.6



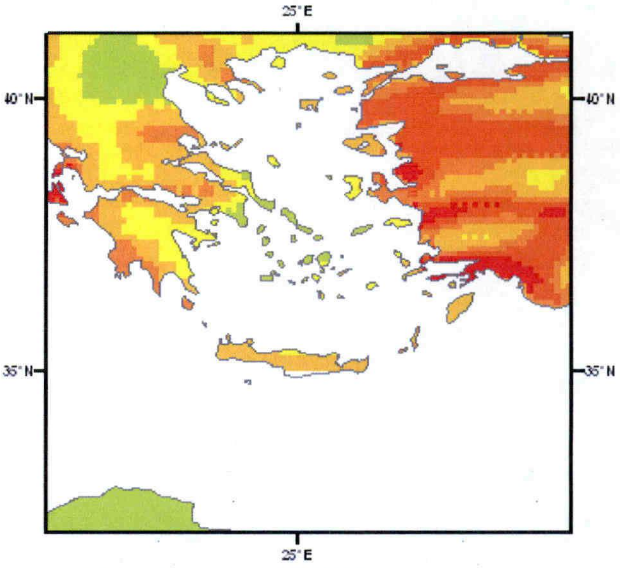
Seismicity (source: BGS World Seismicity Database)



The subducting slab: depth contours (source: Sambridge and Gudmundson, 1998)

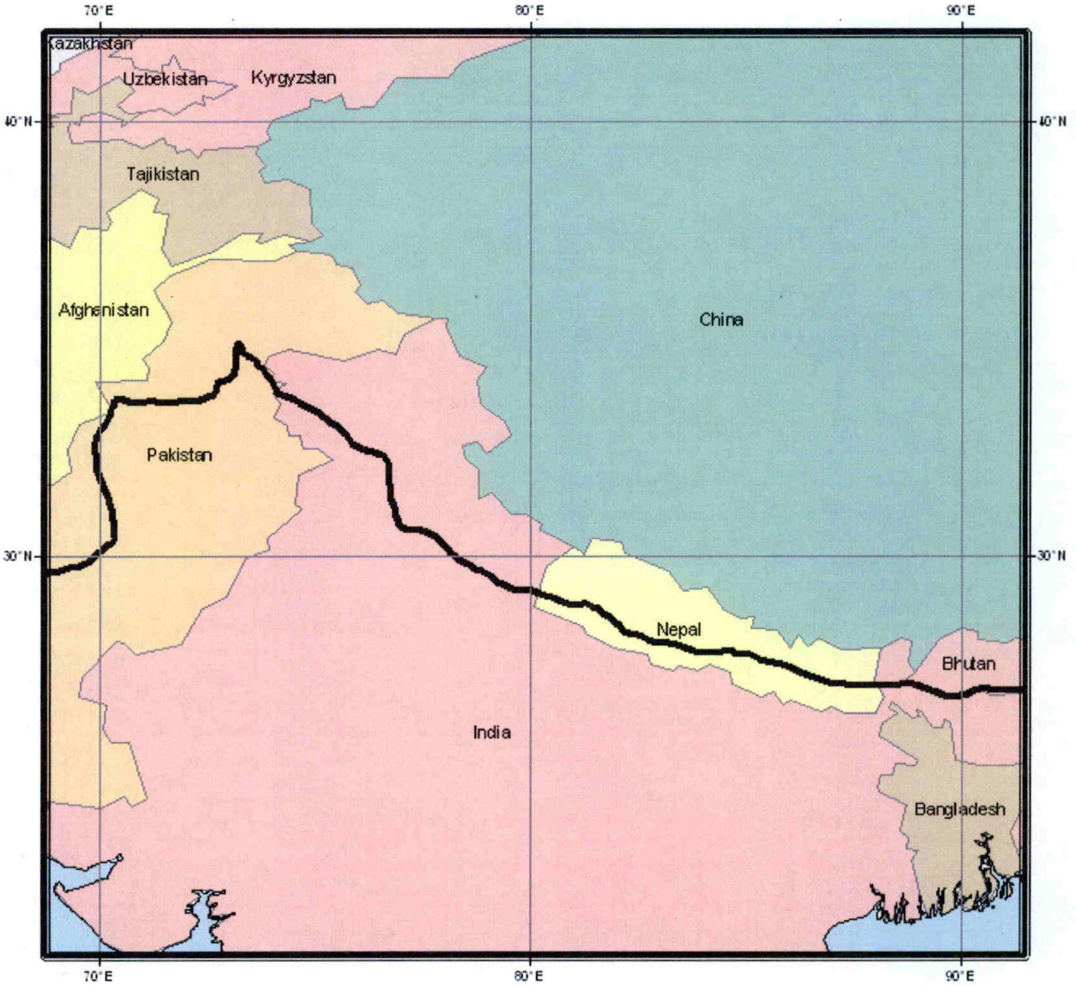


Population distribution for 2002 (source: ESRI)



475 yr seismic hazard (source: GSHAP)

9. Northern India



The continental Indian and Eurasian plates converge in northern India. Although it is not strictly speaking a subduction zone, it does display some characteristics that are similar to island arcs and, as it is a convergent margin with a history of great earthquakes, it is included in this report as a possible area where PSInSAR could be applied.

9.1 Tectonics and structure of the collision zone

The Indian and Eurasian plates converge in northern India/Nepal. This is a continent-to-continent collision zone, but the result is that the Indian Plate is forced beneath the over-riding Eurasian Plate, with thrust earthquakes occurring on two major controlling structures, the Main Central Thrust (MCT) and Main Boundary Fault (MBF).

Convergence was initiated after the closure of Neo-Tethys and the building of the Himalaya (Ni and Barazangi 1984). It has been estimated that since the closure, there has been 2000-3000 km of convergence at the plate boundary. Approximately 300-500 km of this can be accounted for by shortening along the Himalaya mountain belt (Ni and Barazangi 1984). Crustal shortening has given rise to the formation of three major thrust planes: the Main Central Thrust, the Main Boundary Fault and the Main Frontal Thrust (Singh et al 2002), as well as the Indus-Tsangpo suture, which marks the northern limit of the Indian continent (Ni and Barazangi 1984). All of these structures run along the Himalayan belt from east to west, and trend NW-SE.

The global plate motion model of De Mets et al (1990) predicts about 50 mm/yr of northward convergence between India and Eurasia (the India plate moves N13°E relative to the Eurasia plate). However, Larson et al (1999) show that only 18 ± 7 mm/yr of the convergence is accommodated by shortening in the Himalaya. Underthrusting of the Indian Shield beneath the Himalaya is indicated by large earthquakes. GPS measurements suggest that about 20 mm/yr strain is accommodated on a locked zone (~140 km wide and 500 km long) on this system (Larson et al 1999). Parts of this locked region are estimated to have built up as much as 6-15 m of slip potential, which will be relieved in a future M ~ 8 earthquake (Larson et al 1999). The remaining convergence is accommodated by the extrusion of Tibet and south China (Larson et al 1999).

9.2 Seismicity

A belt of seismicity is associated with the convergence zone. The earthquakes are predominantly of moderate magnitude (5-6 Ms) and tend to occur between 10-20 km depth with epicentres between the MCT and MBF (Larson et al 1999). Great earthquakes (Ms > 8) also occur in this region and can be presumed to be predominantly a result of the underthrusting of the Indian Shield. Since 1897, there have been several great earthquakes in the Himalaya. An earthquake in 1897 (8.2 Ms) occurred in the Shillong Plateau, near Assam, another in Kangra (7.5-8.1 Ms) in 1905, one in the Bihar-Nepal region in 1934 (8.3 Ms – see below) and another near Assam in 1950 (8.6 Ms) (e.g. Singh et al 2002).

A 700 km long seismic gap (the Central Seismic Gap) is thought to exist between 88°E (the eastern limit of the 1934 rupture) and 95°E (the western limit of the 1905 rupture zone) (Gahalaut and Chander 1992, Singh et al 2002). This segment remained unbroken during the last episode of strain release and although earthquakes in 1803 and 1833 are likely to have occurred in the gap, they were not big enough to be gap filling (Singh et al 2002). Gahalaut and Chander (1992) point out that the instrumental earthquake record for northern India and the Himalaya is poor and that any proposed seismic gaps may not be accurately located, particularly if they are based on the rupture extents of poorly recorded large historical earthquakes. Bilham (2004) points out that the strain rate in this region is such that the occurrence rate of great earthquakes is sufficiently low with respect to the length of the historical record, that no large earthquake has yet repeated itself within historical times.

9.3 Seismic hazard and vulnerability

Seismic hazard is concentrated around the zone of convergence, i.e. northern India, Nepal, southern China (Tibet). Singh et al (2002) show that if the Central Seismic Gap were to rupture in a single earthquake (8.5 Mw), it is likely that it would cause great loss of life and severe damage to the region, including Delhi (300 km from the MCT and 200 km from the MBF) and its over 10 million inhabitants. Singh et al (2002) point out that the expansion of Delhi means that parts of the city are sited on poorly consolidated fluvial deposits. The authors estimate that the highest hazard is to the area east of Yamuna, and during a large earthquake, liquefaction of the fluvial deposits is likely. This is very believable; in the case of the 15 January 1934 Nepalese earthquake the highest concentration of damage was in the Bihar region of the Ganges plain (due to soil amplification and liquefaction). Since no reports came out of Nepal at that time (the country was closed off from the rest of the world) and the instrumental location was not well determined, it was assumed for many years after that the epicentre of the earthquake was in Bihar. In fact it was distant to the NE, either around 250 km away (Chen and Molnar 1977) or 100 km away (Seeber and Armbruster 1981) according to different studies (Gupta et al 1998).

Other large cities in the region of highest hazard include Lahore, Srinagar and Islamabad. Building standards in the area that would be affected are generally poor, and population density is high. The capacity for a humanitarian disaster is considerable. An exact recurrence today of the 1905 Kangra earthquake could cause up to a third of a million deaths (H. Gupta *pers. comm.* 1995).

9.4 Possibility for PSInSAR application

This region poses some interesting questions. Despite the fact that the ABIC method has not been tried in such a tectonic setting, there seems no reason why it should not be applicable to large-scale thrust faults of this type, and the fact that the interface between the two plates is entirely on land and in a densely populated area should give one excellent scope for obtaining an appropriate dataset, despite the mountainous terrain to the north. Vertical tectonic displacements have already been observed further south, as the collision causes an upward flexural bulge of the Indian Plate. The combination of these flexural stresses with plate boundary slip results in quite a complex pattern of faulting, with all mechanism types possible beneath the Lesser Himalaya (Bilham 2004). Especially given the case that there is considerable uncertainty as to whether a great earthquake along the Himalayan front is in preparation, the use of PSInSAR in North India could achieve some interesting and very useful results.

Magnitude (Ms)

- ○ 8 and above
- ○ 7 - 7.9
- ○ 6 - 6.9
- · 5 - 5.9
- · 4 - 4.9

Depth (km)

- ● 0 - 15
- ● 16 - 34
- ● 35 - 50
- ● 51 - 100
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- ● 301 - 500
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Slab Contours

Depth (km)

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- — 400
- — 450
- — 500
- — 550
- — 600
- — 650

ESRI Population 2002

- ▢ 1
- ▢ 1 - 4
- ▢ 5 - 14
- ▢ 25 - 49
- ▢ 50 - 100
- ▢ 100 - 500
- ▢ 500 - 2,500
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- ◆ City

475 yr Hazard

PGA (m/s2)

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- 🟧 4.0 - 4.8
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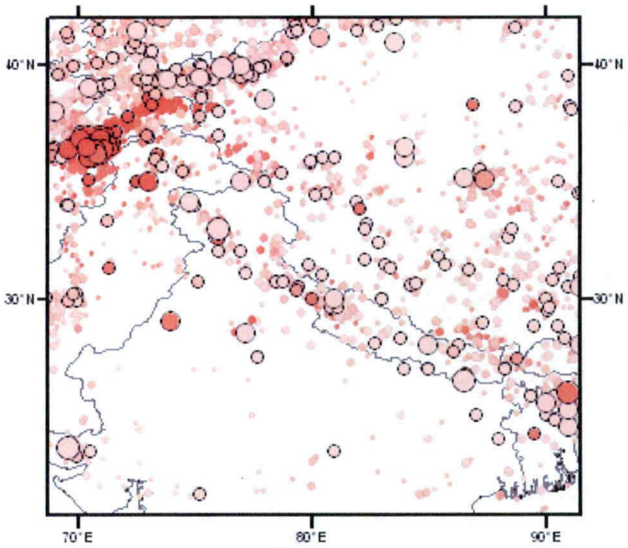
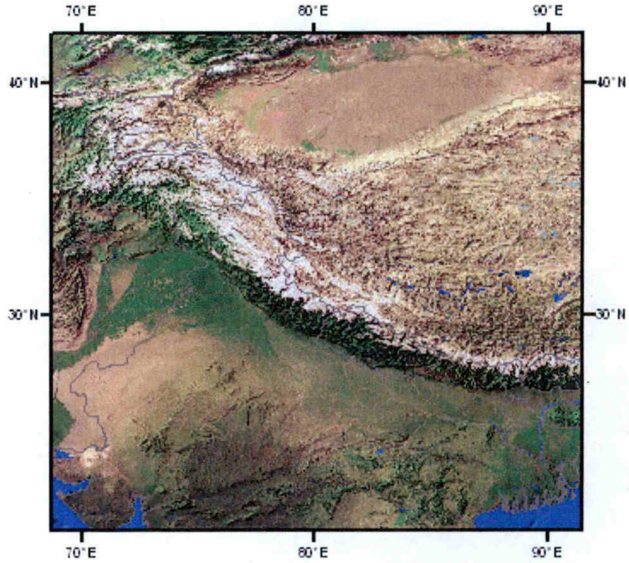
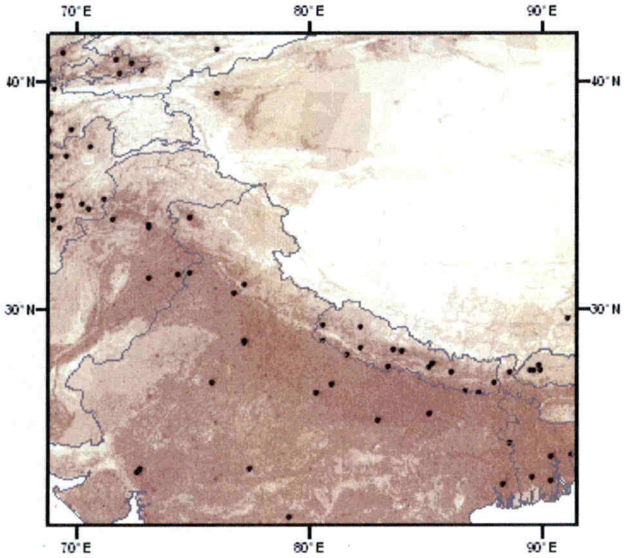


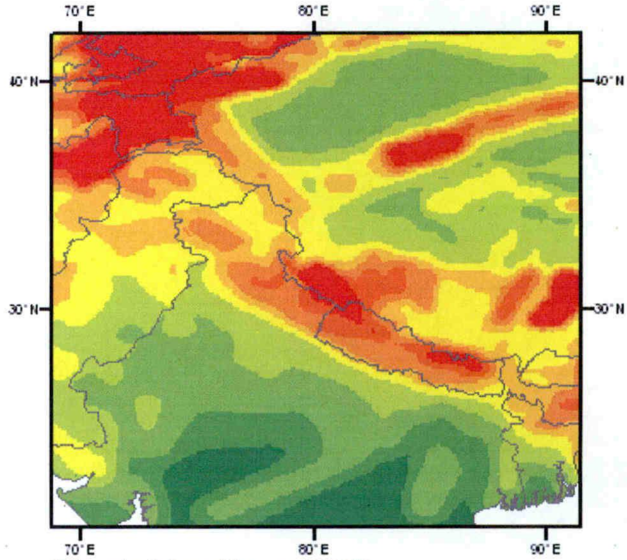
Seismicity (source: BGS World Seismicity Database)



Cloud free world image showing northern India and the Tibetan plateau



Population distribution for 2002 (source: ESRI)



475 yr seismic hazard (source: GSHAP)

10. Conclusions

The suitability of different subduction zones for investigation using PSInSAR has been considered in this report based on several different criteria.

Firstly, the character of the subduction itself. It is assumed here that simple normal subduction presents a more suitable case to study than oblique subduction or complex cases, but this may not be a significant obstacle. It must be remembered that the technique under discussion here is almost untested except in Japan, largely due to the lack of suitable datasets before the possibility of PSInSAR. However, this reason reduces the weight we would give to Alaska and Sumatra.

Secondly, the degree of urbanisation and the land-sea configuration influences the extent to which we would anticipate suitable datasets could be obtained. This largely rules out Alaska, and reduces the attractiveness of the Aegean as a study area. Within Indonesia, Java should be suitable, but other areas less so.

It is possible we may be overstating this factor as a limitation. Yoshioka et al (2004) obtained meaningful results in Mexico with a just a handful of GPS stations. However, Yoshioka et al (2001) in Cascadia, with a greater number of GPS stations, was not able to resolve the data adequately. Clearly, the more data points the better, but what is the minimum number of points needed for a satisfactory result may vary from case to case, and may not be predictable before the start of any project. We envisage one of the key advantages of PSInSAR is its potential to yield a dense net of data for interpretation, and hence we prioritise those areas in which this can best be obtained over a large area.

The potential impact of earthquake hazard in the regions examined varies. Regions like Cascadia or Japan, where economic development is highly advanced, tend to be characterised by relatively low vulnerability (buildings are generally well-constructed) but with enormous amounts of financial exposure. In regions like Central and South America or Northern India, especially the latter, there is particular concern about the humanitarian aspects of a potential large earthquake, where large concentrations of people live in buildings that may be quite vulnerable.

Some regions have particular interest because there are particular reasons to consider that a large earthquake may be impending. This particularly applies to Cascadia, Japan and Northern India, and may apply to parts of South and Central America and the Aegean.

Northern India is a special case because the region is entirely on land, making it particularly suitable for obtaining a good dataset.

For further studies, our order of precedence would be as follows:

1. Japan: Expand the test areas already examined westwards and northeastwards, taking in especially the Kanto area.
2. Cascadia: The possibility of a large earthquake in this area is a high-profile issue. It is significant that the ABIC method has been attempted here already, with poor results because the GPS data were insufficient.
3. Northern India: This is a very interesting case for a variety of reasons already discussed.
4. Central America: Very suitable. The ABIC method has been applied here already with limited GPS data, in a small area (the Guerrero seismic gap).
5. South America: Very suitable.

6. Aegean: Moderately suitable. Would be interesting as the one European case.
7. Indonesia: At least partly suitable.
8. Alaska: Low priority.

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